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Assessment of Literature Related to Combustion Appliance Venting Systems

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ABSTRACT

In many residential building retrofit programs, air tightening to increase energy efficiency is constrained by concerns about related impacts on the safety of naturally vented combustion appliances. Tighter housing units more readily depressurize when exhaust equipment is operated, making combustion appliances more prone to backdraft or spillage. Several test methods purportedly assess the potential for depressurization-induced backdrafting and spillage, but these tests are not robustly reliable and repeatable predictors of venting performance, in part because they do not fully capture weather effects on venting performance. The purpose of this literature review is to investigate combustion safety diagnostics in existing codes, standards, and guidelines related to combustion appliances. This review summarizes existing combustion safety test methods, evaluations of these test methods, and also discusses research related to wind effects and the simulation of vent system performance. Current codes and standards related to combustion appliance installation provide little information on assessing backdrafting or spillage potential. A substantial amount of research has been conducted to assess combustion appliance backdrafting and spillage test methods, but primarily focuses on comparing short-term (stress) induced tests and monitoring results. Monitoring, typically performed over one week, indicated that combinations of environmental and house operation characteristics most conducive to combustion spillage were rare. Research, to an extent, has assessed existing combustion safety diagnostics for house depressurization, but the objectives of the diagnostics, both stress and monitoring, are not clearly defined. More research is also needed to quantify the frequency of test “failure” occurrence throughout the building stock and assess the statistical effects of weather (especially wind) on house depressurization and in turn on combustion appliance venting. Incorporating weather variations and house ventilation system characteristics in existing simulation software may assist such analyses and with developing a more reliable diagnostic for use on-site.

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EXECUTIVE SUMMARY

The exhaust from residential combustion appliances contains air pollutants and high levels of moisture that must be conveyed to the outdoors to maintain acceptable indoor air quality. Exhausting combustion products from the appliance outlet, through the vent system to the outdoors, requires a net positive available draft at the appliance outlet (D_a), according to the physical relationship described in Equation E.1:

$$D_a = D_t - \Delta p - D_p. \tag{E.1}$$

In this equation, D_t is the upward natural draft produced by the buoyancy of hot gases in the vent system relative to air surrounding the vent (theoretical draft), Δp is the sum of pressure losses due to flow resistance in the vent system (i.e., vent inlet, outlet, fitting, and friction losses), and D_p is the depressurization of the space surrounding the combustion appliance relative to outdoors where the chimney discharges [1].

Retrofits to increase energy efficiency can interfere with natural draft appliance venting. In particular, air sealing creates tighter buildings that more readily depressurize. Depressurization can vary over time and depends on building envelope and interior partition airtightness, door and window opening, weather-related natural driving forces (wind and indoor-outdoor temperature effects), and on mechanical driving forces due to the operation of devices such as exhaust fans, clothes dryers, and other combustion appliances such as unsealed fireplaces. Installation or upgrades of kitchen and bath exhaust fans to meet residential ventilation requirements (e.g., ASHRAE Standard 62.2) can further depressurize homes, making combustion appliances more prone to backdrafting (when flow is reversed in the chimney during appliance operation) or spillage (combustion product entry into the building).

Currently, there are two main approaches to assess whether a natural draft appliance that is inside a home is susceptible to hazardous spillage of combustion gases: (1) by monitoring appliance operation and parameters that indicate the occurrence of backdrafting or spillage, and (2) by conducting measurements under induced conditions and extrapolating results to predict performance under normal use, also known as stress tests.

Monitoring for backdrafting and spillage under normal use conditions typically offers more reliable results and inherently measures the performance over a broader range of use and weather conditions relative to stress tests. However, monitoring methods can be expensive due to the cost of equipment, its set-up and removal, and subsequent data analysis. Additionally, collecting data in such a way is not practical for contractors to be effective and efficient when assessing safety for individual homes.

Stress tests typically seek to induce "worst-case" conditions by operating all exhaust fans at their highest settings and opening or closing interior doors to achieve the highest level of depressurization in the area of the house containing the combustion appliance of interest. The area containing the appliance is referred to as the *combustion appliance zone* or CAZ. Although the stress test methods are less costly and time consuming than monitoring, they can still require two or more person-hours of effort by trained technicians. They only indicate the possibility of backdrafting and do not address the frequency of the factors that contribute to depressurization-induced backdrafting or spillage. These factors include coincident operation of exhaust fans and the appliance, and the effects of weather variations. The stress tests were explicitly developed to assess venting performance during cold-weather venting conditions, making them inappropriate for assessing venting during warm weather conditions, and are especially susceptible to wind-induced variations of depressurization. As a result, these methods sometimes fail: they indicate that an appliance should not be operated even though backdrafting is not actually problematic; in other cases, they indicate that it is permissible to operate an appliance even though the appliance does not robustly vent throughout the range of local weather conditions.

This literature review is the first step towards developing a more robust and efficient combustion safety diagnostic method. The purpose of this review is to summarize the metrics, tests, and diagnostic protocols currently used to assess combustion safety, and to document their technical basis. This literature review builds upon Berkeley Lab's Residential Commissioning Literature Review, published in 2000, and focuses on relevant research and publications related to stress test and monitoring performance, vent system resistance, wind effects on test methods and depressurization, and simulations of vent system performance. Important studies related to backdrafting and combustion spillage are also identified.

Current codes and standards related to combustion appliance installation and venting (NFPA 54 and California Title 24, Part 2.5) provide little information on assessing backdrafting or spillage potential. A draft test is recommended after an appliance is installed, but it is only required that the appliance establish draft within five minutes after startup. No protocols are provided for appliances that do not establish draft. The codes also include vent-sizing requirements intended to ensure that combustion appliances vent properly. However, not all venting systems meet current codes and standards, and upgrading systems to meet these codes is not consistently included in energy retrofits.

A substantial amount of research has been conducted to assess combustion appliance backdrafting and spillage test methods. Much of the research compares results from stress tests to one-week of monitoring and these comparisons were performed on houses dissimilar to the majority of California houses. This research generally concludes that stress-induced tests should be interpreted with caution, as they tend to over predict the number of spillage prone houses and results vary significantly with outdoor conditions. The authors of one study recommended that an appliance should have to fail multiple (specific number not specified) stress tests before it is considered spillage prone. Results from monitoring in homes that failed stress tests found that events of sustained spillage were extremely rare. Extensive monitoring has not been conducted in houses that pass stress-induced tests to assess the rate at which appliances passing stress tests actually backdraft or spill. In the rare instance that spillage was observed in monitored homes, events typically lasted 1 to 2 minutes during initial operation of the appliance. In one case, spillage was observed continuously during appliance operation. The study concluded that the spillage was a result of an improperly sized venting system. Two studies concluded that properly sized venting systems, complying with existing codes and standards, were less likely to spill. These studies also recommended that emphasis be placed on improving venting performance to prevent combustion spillage.

When monitoring houses, several authors indicate that vent pressure is not a good indicator of spillage, as positive pressures often result from downdrafting (combustion appliance off) and not backdrafting or spillage. Additionally, temperature monitored in the spillage zone may be affected by thermal radiation from gases flowing near the draft diverter, providing false spillage measurements. Several authors also recommend monitoring be conducted for longer periods of time before making definitive conclusions about the accuracy of the stress-induced test results. Overall, the monitoring results indicate that combinations of environmental and house operation characteristics most conducive to combustion spillage are rare.

Research investigating the effects of weather variation on stress-induced tests is limited. One study showed houses were more likely to fail stress-induced tests during low wind speeds rather than during high wind speeds. This study did not find a definitive correlation between outdoor temperature and stress-induced tests, but a different study showed spillage failure increasing significantly when outside temperatures exceeded 40°F.

The objectives of these test methods, both stress and monitoring, are not clearly defined. Implicitly the tests apply a dichotomous criterion, with any occurrence of backdrafting or spillage regarded as a failing condition. In practice, the likelihood and frequency of such events in any given home has a statistical element that is essential to the health and safety risk. Likewise, variations in the pollutant generation characteristics of various appliances impact the actual risks associated with backdrafting and spillage. Yet none of the current diagnostic procedures address the statistical nature of the risk, nor do they account for variations in risk associated with differences in pollutant generation across appliances.

Existing simulation software can assist with design and analysis of residential combustion appliance venting systems. In particular, using this software to predict backdrafting or spillage using whole house system inputs (e.g., envelope airtightness, combustion appliance and ventilation system operation, chimney or vent design, weather effects) could be useful for creating a more robust diagnostic method for field use. However, the software is not currently being used for this purpose.

In summary, several measures, such as vent sizing codes and combustion safety diagnostics, have been put in place with the intent to prevent combustion spillage. Research, to an extent, has also assessed existing combustion safety diagnostics for house depressurization. However, more research is needed to quantify the frequency of test “failure” occurrence throughout the building stock and to assess the statistical effects of weather (especially wind) on house depressurization and in turn on combustion appliance venting. Incorporating weather variations and house ventilation system characteristics in existing simulation software may assist such analyses and with developing a more reliable diagnostic for use on-site.

ACRONYMS AND SYMBOLS

AGA	American Gas Association
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CAS	Combustion Appliance Safety
CAZ	Combustion Appliance Zone
CFD	Computational Fluid Dynamics
CGSB	Canadian General Standards Board
CMHC	Canada Mortgage and Housing Corporation
CO	Carbon monoxide
CO_2	Carbon dioxide
CSST	Corrugated Stainless Steel Tubing
CVEP	Cold Vent Establishment Pressure
D_a	Available Draft (Pa)
D_p	Depressurization (Pa)
D_t	Theoretical Draft (Pa)
ELA	Effective Leakage Area
GTI	Gas Technology Institute
H	Height of the vent section
HRV	Heat Recovery Ventilator
IFGC	International Fuel Gas Code
LDC	Local Distribution Companies
NFPA 54	National Fuel Gas Code (National Fire Protection Association Standard 54)
NGAT	Natural Gas Appliance Testing
N_s	Total number of vent sections in the vent connector or common vent
P_{nat}	Draft in each vent region
RESNET	Residential Energy Services Network
RMS	Root Mean Square
UCM	Unattended Continuous Monitoring
w.c.	Water Column
Δp	Flow losses (Pa)
ρf	Mean density of vent gas in the vent section i
ρo	Density of air outside the vent at the elevation of the vent section

GLOSSARY

The following are definitions of terms used in this literature review. The definitions come from the National Fuel Gas Code 2012 [39], unless noted otherwise.

Term	Definition
ACH50	The Air Changes per Hour (ACH) at 50 Pa. Used as a measure of building airtightness.*
Appliance Flue	The passage(s) within an appliance through which combustion products pass from the combustion chamber of the appliance to the draft hood inlet opening on an appliance equipped with a draft hood or to the outlet of the appliance on an appliance not equipped with a draft hood.
Backdrafting	The reversal of the ordinary (upward) direction of air flow in a chimney or flue when vented combustion appliances are operating.
Category I Vented Appliance	An appliance that operates with a *non-positive* vent static pressure and with a vent gas temperature that *avoids* excessive condensate production in the vent.
Category II Vented Appliance	An appliance that operates with a *non-positive* vent static pressure and with a vent gas temperature that *can cause* excessive condensate production in the vent.
Category III Vented Appliance	An appliance that operates with a *positive* vent static pressure and with a vent gas temperature that *avoids* excessive condensate production in the vent.
Category IV Vented Appliance	An appliance that operates with a *positive* vent static pressure and with a vent gas temperature that *can cause* excessive condensate production in the vent.
Central Furnace	A self-contained appliance for heating air by transfer of heat of combustion through metal to the air and designed to supply heated air through ducts to spaces remote from or adjacent to the appliance location.
Chimney	One or more passageways, vertical or nearly so, for conveying flue or vent gases to the outdoors.
Chimney Flue	The passage(s) in a chimney for conveying the flue or vent gases to the outdoors.
Common Vent	That portion of a vent or chimney system that conveys products of combustion from more than one appliance.
Direct Vent Wall Furnace	A system consisting of an appliance, combustion air, and flue gas connections between the appliance and the outdoor atmosphere, and a vent cap supplied by the manufacturer and constructed so that all air for combustion is obtained from the outdoor atmosphere and all flue gases are discharged to the outdoor atmosphere.
Draft Hood	A draft hood acts as a pressure break between the vent system and the appliance and eliminates stack action. Without draft, the vent could experience excessive draft, flame instabilities, and possibly pilot outage.
Downdrafting	The reversal of the ordinary (upward) direction of air flow in a chimney or flue when no vented combustion appliances are operating.

Duct Furnace	A furnace normally installed in distribution ducts of air-conditioning systems to supply warm air for heating. This definition applies only to an appliance that, for air circulation, depends on a blower not furnished as a part of the furnace.
Flue Gases	Products of combustion plus excess air in appliance flues or heat exchangers. This does not include dilution air from a draft diverter.
Gas Vent	A passageway composed of listed factory-built components assembled in accordance with the manufacturer's installation instructions for conveying flue gases from appliances to the outdoors.
Masonry Chimney	A field-constructed chimney of solid masonry units, bricks, stones, listed masonry chimney units, or reinforced Portland cement concrete, lined with suitable chimney flue liners (Note: an exterior masonry chimney is exposed to the outdoors on one or more sides below the roofline).
Metal Chimney	A field-constructed chimney of metal.
Regulator Vent	The opening in the atmospheric side of the regulator housing permitting the in and out movement of air to compensate for the movement of the regulator diaphragm.
Spillage**	Entry of combustion products into a building from dilution air inlets, vent connector joints, induced draft fan case opening, combustion air inlets, or other locations in the combustion or venting system of a vented combustion appliance (boiler, fireplace, furnace, or water heater), caused by backdrafting, vent blockage, or leaks in the venting system.
Type B Gas Vent	A vent for venting gas appliances with draft hoods and other Category I appliances requiring Type B gas vents.
Type B-W Gas Vent	A vent for venting listed wall furnaces.
Type L Gas Vent	A vent for venting appliances requiring Type L vents or appliances requiring Type B gas vents.
Vent	A passageway used to convey flue gases from appliances or their vent connectors to the outdoors.
Vent Connector	The pipe or duct that connects a fuel gas-burning appliance to a vent or chimney.
Vent Gases	Products of combustion from appliance plus excess air, plus dilution air in the venting system above the draft hood or draft regulator.
Venting	The conveyance of combustion products to the outdoors.

* Taken from "Tectite Building Airtightness Test" by The Energy Conservatory
** Taken from ASTM E1998 [3]

CHAPTER 1: Introduction

Concerns about combustion appliance safety are interfering with efforts to improve energy efficiency through residential building retrofits. A key concern is that venting of combustion exhaust from natural draft appliances within the house can be impeded when the house is depressurized, meaning the house has a lower pressure than the outdoors. Since air moves from areas of higher pressure to lower pressure, the depressurization of an inside space relative to the outdoors creates a driving force for air to move from outdoors to indoors through any available opening in the pressure boundary, including the vent of a natural draft – sometimes called an atmospherically vented – combustion appliance. The force of this downward flow is related to the magnitude of depressurization. When depressurization is large in magnitude, the driving flow can overcome the upward (buoyant) force of the hot exhaust gases that drive the normal venting of appliance exhaust. Downward flow occurring when the appliance burner is not operating is called downdrafting. Downdrafting when the burner is operating is called backdrafting. Backdrafting causes the combustion exhaust from the flue to spill into the house. Spillage of exhaust gases containing high levels of pollutants, with carbon monoxide (CO) being the principal concern, presents serious health, and in extreme cases, life-safety hazards. Owing to the potentially catastrophic impacts - including serious illness and death from CO poisoning - the building performance industry promotes extreme caution to avoid backdrafting and spillage from natural draft appliances. CO is not the only pollutant of concern, however: others include nitrogen dioxide, particles, and water vapor.

Downdrafting and backdrafting of combustion appliances are often a result of depressurization. Depressurization of buildings or areas within buildings can occur naturally from wind forces and from flow patterns that result from indoor-outdoor temperature differences. For example, when naturally ventilated buildings are heated in winter, buoyancy causes the higher temperature air to rise and exit through the upper part of the structure. The air exiting through the top creates a negative pressure in the lower part of the building that pulls in replacement air from outdoors (or potentially from the subsurface when the basement is subterranean – a house configuration that is common in some parts of the U.S. but not in California). This process of induced inward flow across a pressure boundary is called infiltration.

Mechanical systems within the house can also cause and contribute to depressurization. Exhaust fans that move air from the interior of the house to outside typically are the most important contributors to depressurization. Air leakage in heating and cooling duct systems can also contribute to depressurization. Depressurization caused by a fan increases as the amount of air the fan moves increases (roughly to the power 1.5). The largest exhaust fans within houses are typically the clothes dryer and range hood (or other cooking exhaust fan). Clothes dryers connected to lint-free ducts can exhaust as much as 200 cubic feet per minute (cfm). Many range hoods have multiple fan speeds to produce several different flow rates and there is a very large range of maximum flow rates (at the highest speed) for available hoods. Basic range hoods typically have up to a 150 cfm capacity under ideal conditions. Range hoods costing in the range of $150 to $350 typically have upper bound airflows of 200 cfm to 300 cfm. Some microwave range hoods can exhaust air in excess of 300 cfm at high speed and “performance” hoods costing in excess of $400 have the capacity to exhaust more than 500 cfm from the house. Downdraft cooktop exhaust systems are usually designed to deliver in excess of 300 cfm when they have low-resistance exhaust ducts. Bath fans typically are rated for flows of 50 cfm or greater and continuous exhaust fans designed to comply with building ventilation standards typically range from about 40 cfm to 80 cfm. When supply ducts are outside of the pressure boundary (e.g., in the attic or crawl space), leakage from these ducts acts similarly to an exhaust fan.

If the building pressure boundary is very leaky, relatively small pressure differences can produce relatively large infiltration airflows. The pressure boundary for the interior living space may be at the building envelope or at partitions within the shell, depending on construction and any air sealing that has been done. The attic in particular may be included within or be outside the pressure boundary. Sealing large airflow pathways, including large or long cracks and seams in the boundary, reduces the air infiltration that occurs at any specific level of depressurization. Thus, under the same weather conditions and the same indoor-outdoor temperature difference with no exhaust fan use, a more airtight house will have lower infiltration. The pressure vs. airflow relationship also can be driven by mechanical systems. Increasing exhaust flows in a house (with a given level of airtightness) will increase depressurization. If the house has a leaky pressure boundary, much larger mechanically induced airflows are required to produce substantial depressurization. Conversely, if the house is made more air tight, the same amount of exhaust flow will lead to a higher level of depressurization.

Recognizing that the thermal conditioning of infiltrating air can account for a large fraction of annual heating and cooling energy use in residences, air tightening has become a cornerstone of residential energy efficiency retrofit practice and programs. Yet there is also recognition that the increased air tightness and the addition of kitchen, bath, or general exhaust fans will increase the frequency of depressurization that could induce combustion appliance backdrafting and spillage. The response of the low-income weatherization programs and many other retrofit programs targeted at the general public has been to limit air tightening to avoid creating backdrafting hazards. This is the “first, do no harm” principle.

Many tests and other assessment protocols have been developed to identify appliances and houses that present a backdrafting hazard. The two most common test methods for assessing combustion safety are short-term (stress) tests and monitoring. Stress tests, performed under induced conditions, indicate the possibility of backdrafting and capture the effects of outdoor temperature and wind on venting potential only at the time of the test (i.e., a “snapshot” in time). Additionally, these test methods may produce misleading results: failing houses when backdrafting is not actually problematic or passing houses that may be problematic under some operational conditions. Monitoring, conducted under natural conditions, can capture venting performance over a range of weather conditions, but is time consuming and expensive due to the cost of equipment, equipment set-up and removal, and data analysis. The robustness of monitoring increases with the duration and range of weather and operational conditions during which monitoring occurs, but the cost also increases with deployment time.

As described above, backdrafting and spillage result from a confluence of contributing physical factors that include appliance characteristics and location; vent materials, design, and configuration; air tightness of the building in general and the combustion appliance zone in particular; location-specific weather conditions; characteristics of other mechanical systems in the house; and use patterns of the appliance and other mechanical systems. Since backdrafting and spillage occur only with some confluence or coincidence of physical processes, it is relevant to consider these hazards as having statistical as well as physical characteristics.

Surprisingly, there is no clearly-stated, statistically-rooted risk mitigation target for existing combustion safety diagnostic protocols. Theoretically, the target could be one designed around extreme caution and zero risk (i.e., to identify appliance and venting installations that could backdraft and spill under possible, if highly unlikely combinations of operation and weather). Or the target could be to reduce risk below some level that is considered tolerable (i.e., based on an expected frequency or likelihood of any spillage occurring over the course of a year). Induced stress tests that create nominal “worst case” conditions could be understood as seeking zero risk tolerance. On the other hand, some stress tests and long term monitoring approaches allow (do not treat as failures) short occurrences of transient spillage associated with main burner ignition. Additionally, these tests do not address the health risk associated with allowable spillage. Instead, the depressurization threshold represents the spillage hazard.

Specifying a clear risk mitigation objective is important when trying to assess whether an appliance and venting configuration is problematic, and especially to assess whether a test is effective at finding problematic installations. For the specific objective of no sustained spillage under any circumstance, monitoring would have to be conducted over a long enough period to capture seasonal variations in equipment use and weather. And, the effectiveness of a stress test would need to be assessed against such a long-term monitoring record.

For a no-risk standard, there are two essential questions that are relevant to assessing specific tests.

(1) Does the test “fail” (or identify as problematic) appliance and venting installations that do not produce sustained backdrafting and spillage in use?

(2) Does the test “pass” (or not identify as problematic) some appliance and venting installations that actually produce sustained backdrafting and spillage during use?

The former can be characterized as misleading test failures; the latter can be characterized as misleading passes. The concept of a misleading test result is also relevant to probability-based metrics. If the risk mitigation target is, for example, a maximum of three sustained spillage events per year each not lasting more than one hour, then theoretically it would be misleading to characterize as a failure an appliance and venting configuration that spills only once per year.

One approach to overcoming some of the limitations associated with stress tests and monitoring is to use physics-based computer models to simulate the operation of an appliance and other exhaust systems over a typical location-specific weather year. The model must include the physical characteristics of the appliance and vent system (e.g., combustion gas discharge temperature, vent material, pressure losses, and flue type), house air tightness, airflow rates of exhaust devices, heating and cooling system duct leakage, and the configuration of the systems in the house. Also needed are appliance and exhaust system use patterns. In practice, many of these parameters have a probabilistic nature: that is, they vary over time or from house to house. With all of this information and a model that appropriately captures the physical relationships, one could calculate the probable maximum depressurization that would be expected and then predict the occurrence and frequency of sustained backdrafts and spillage. This information would also provide input for defining air tightness, air change rate, and unbalanced ventilation constraints that enable combustion appliances to vent properly while minimizing associated energy penalties.

The objective of this project is to provide the research basis for a more robust method for assessing combustion safety; this literature review is the first critical step. In particular, this report summarizes existing codes and standards for developing venting systems (Chapter 2), combustion safety test methods (Chapter 3), research assessing the combustion safety test methods (Chapter 4), and patents for devices measuring backdrafting and spillage (Chapter 5). Additionally, research on the effects of wind on house depressurization and vent termination are discussed (Chapter 6), because wind can have a significant effect on venting performance and test results. Information on existing simulation software for venting systems is also provided and validation reports, if available, are summarized (Chapter 7). Existing simulation software may provide a useful basis for creating tools that can predict venting performance in combination with other house characteristics. Gaps in existing knowledge that require further research and development are highlighted (Chapter 8).

CHAPTER 2: Codes and Standards for Vent Systems

Several codes and standards apply to combustion appliances and their vent systems. The National Fuel Gas Code [39] provides information regarding installation and operation of gas appliances in residential buildings. It also provides guidelines for appropriately sizing vent systems and provides a recommended combustion safety test, where a smoke stick or match is used to assess if a combustion appliance is drafting properly. Although the National Fuel Gas Code recognizes that operation of exhaust fans and other appliances can create venting problems for combustion appliances, it does not provide a recommended solution. Other National Fire Protection Association Codes [40, 41, 42] provide guidelines for designing, constructing, and installing metal and masonry chimneys.

Parts of California's Title 24 Building Code that apply to combustion appliance vent systems [9, 10, 11] quote and reference the information published in the National Fuel Gas Code. The California Residential Compliance Manual [12], however, requires that combustion appliances follow the standards in ASHRAE 62.2.

ASHRAE Standard 62.2 [2] primarily addresses residential house ventilation, but also requires that all combustion and solid-fuel burning appliances must be provided with adequate combustion and ventilation air. For naturally-vented combustion appliances located inside the "pressure boundary" (primary air enclosure separating indoor and outdoor air), the total net exhaust flow of the two largest exhaust fans shall not exceed 15 cfm per 100 ft^2 of occupiable space when operating at full capacity. If exhaust flow exceeds this limit, then the exhaust fan flow must be reduced or compensating outdoor airflow must be provided. The 2008 Residential Compliance Manual [12] references ASHRAE 62.2 and provides the additional suggestion of moving the combustion appliance outside the pressure zone to solve problems with exhaust flows exceeding the limit.

Further details regarding codes and standards that address combustion appliance safety and vent systems are presented in the following sections.

National Fuel Gas Code

The current (2012) National Fuel Gas Code (NFPA 54) [39] lists criteria for the installation and operation of gas piping and gas equipment in residential buildings. The code was originally issued in 1974 (although related efforts began as early as 1913); in 1988, the scope of the code was expanded to include piping systems up to and including 125 psi. In 2002, the code was revised to include requirements for air supplied to combustion appliances and ventilation. The sizing of the gas piping system was also updated. In 2006, expanded steel, copper, and polyethylene pipe sizing tables were included and requirements for appliance shutoff valves were also revised. In 2009, press-connect fittings for gas piping systems were allowed. New requirements for bonding corrugated stainless steel tubing (CSST) piping systems were also incorporated and the sizing table for CSST was expanded. Outdoor decorative appliances and new requirements to seal the annular space around the side-wall vent penetrations were also included. The 2012 edition includes changes on purging fuel gas piping. Additionally, the requirements for bonding of CSST were revised. New requirements for overpressure protection for regulators exceeding 2 psi were added and requirements for "Room larger in comparison with size of appliance" were deleted because changes in boiler and furnace design make this no longer relevant.

NFPA 54 provides installation, design, and sizing guidelines for combustion appliance vents. With the intent of ensuring an adequate supply of combustion air, the code specifies a minimum indoor volume of 50 ft^3/1000 Btu/hr (4.8 m^3/kW) when the air infiltration rate is not less than 0.40 air changes per hour (ACH). If the air infiltration rate is less than 0.40 ACH, then the required indoor combustion air volume is calculated using equations outlined in Chapter 9 of the code. The code also states that combustion appliances cannot be installed in bedrooms or bathrooms unless the room meets the indoor combustion air volume requirements.

All combustion appliances must be connected to venting systems, except the following: ranges; built-in domestic cooking units listed and marked for optional venting; listed hot plates and laundry stoves; dishwashers; refrigerators; counter appliances; room heaters listed for unvented use; direct gas-fired make-up air heaters; other appliances listed for unvented use and not provided with flue collars; and specialized appliances of limited input such as laboratory burners or gas lights.

The code requires that venting systems satisfy the draft requirements set by the appliance manufacturer. When selecting appropriate vents for combustion appliance venting systems, the code divides combustion appliances into the following four categories: Category I – an appliance that operates with a *non-positive* vent static pressure and with a vent gas temperature that *avoids* excessive condensate production in the vent; Category II – an appliance that operates with a *non-positive* vent static pressure and with a vent gas temperature that *can cause* excessive condensate production in the vent; Category III – an appliance that operates with a *positive* vent static pressure and with a vent gas temperature that *avoids* excessive condensate production in the vent; and Category IV – an appliance that operates with a *positive* vent static pressure and with a vent gas temperature that *can cause* excessive condensate production in the vent. Most residential combustion appliances, including water heaters, furnaces, and ovens, are listed as Category I appliances. Some furnaces with higher exhaust temperatures, however, are listed as Category II appliances.

Most Category I gas-fired appliances use round or oval double-wall Type B gas vents, which generally have an aluminum inner wall and galvanized steel outer wall (Type L vents, which are similar, but have a stainless steel inner wall, can also be used). Vented wall furnaces use an oval-only double-wall Type B-W gas vent. In some cases, the vents pass through a masonry chimney.

Termination points of chimneys for residential or low-heat appliances are required to extend at least 3 ft above the highest point where it passes through the roof and at least 2 ft higher than any portion of the building within a horizontal distance of 10 ft. A chimney for Category II appliances is required to extend at least 10 ft higher than any portion of any building within 25 ft. Masonry chimneys are required to extend at least 5 ft above the highest connected appliance draft hood or flue collar.

Gas vents 12 inches or less in diameter and located at least 8 ft from a vertical wall or similar obstruction are required to terminate above the roof. Gas vents that are over 12 inches in diameter or are located less than 8 ft from a vertical wall or similar obstruction shall terminate not less than 2 ft above the highest point where they pass through the roof and not less than 2 ft above any portion of a building within 10 ft horizontally. A Type B or a Type L gas vent shall terminate at least 5 ft (1.5 m) in vertical height above the highest connected appliance draft hood or flue collar. A Type B-W gas vent shall terminate at least 12 ft in vertical height above the bottom of the wall furnace. All gas vent terminations must have a vent cap. Further details regarding gas vent termination can be found in Chapter 12.

Tables in Chapter 13 of NFPA 54 provide sizing guidelines for different types of combustion appliances. According to Bohac and Cheple [7], if vents are sized and lined according to tables in Ch. 13 in NFPA 54, then appliances will vent properly. Details for the Bohac and Cheple research can be found in Chapter 3 of this literature review. It should be noted that the minimum allowable vent diameter is 3 inches.

Guidelines for vent connectors when two or more appliances are connected to a single vent are also presented. To ensure proper venting, NFPA 54 requires vents to slope upward at least ¼ inch per horizontal foot. Additionally, the connectors shall be attached to the vertical portion of the chimney or vent at an angle of 45 degrees or less relative to the vertical position.

A procedure for performing a safety inspection of existing installed combustion appliances is given in Appendix G of NFPA 54. Surprisingly, the code states that the safety inspection is a recommended but not required procedure. Most of the safety inspection addresses installation of the combustion appliance and checking for gas leaks. One line in the safety inspection addresses combustion spillage and states: “Test for spillage at the draft hood relief opening after five minutes of main burner operation. Use the flame of a match or candle or smoke.” The safety inspection recommends that this “test” be repeated when other combustion appliances, located in the CAZ, are operated at full capacity. NFPA 54 recognizes that operation of exhaust fans, ventilation systems, clothes dryers, or fireplaces can create conditions that result in improper venting of a combustion appliance, but it does not provide further instructions for assessing or addressing such situations.

International Fuel Gas Code

The current (2012) International Fuel Gas Code (IFGC) [31] establishes minimum regulations for the design and installation of fuel gas systems and gas-fired appliances. The code emphasizes performance of appliances while aspiring to safeguard public health. Although this code is considered independent of NFPA 54 [39], the IFGC provides the same requirements for installing, designing, and sizing vents for combustion appliances as does NFPA 54. One difference between the IFGC and NFPA 54 is that the IFGC does not provide as strict requirements for required volume of indoor combustion air.

A safety inspection for installed gas appliances is recommended in Appendix D of the IFGC. The safety inspection is similar to the inspection published in NFPA 54 [39], but recommends that the procedure be performed prior to modifying the appliance or modifying the existing installation. Additionally, the IFGC states that appliances deemed unsafe for operation should be “shut off.” The procedure for making the safety inspection is the same procedure outlined in Appendix G of NFPA 54 [39].

NFPA 211

NFPA 211 [40] is a standard for chimneys, fireplaces, vents (for gas appliances), and solid fuel-burning appliances. This standard applies to the design, installation, maintenance, and inspection of all chimneys, fireplaces, and venting systems. The standard also includes installation, maintenance, and inspection of solid fuel-burning appliances, which is not included in NFPA 54 [39]. NFPA 211 primarily focuses on removal of exhaust gases and the reduction of fire hazards associated with the construction and installation of chimneys fireplaces, and venting systems. This standard recommends using approved engineering methods, such as the vent capacity tables in NFPA 54, manufacturer’s instructions, the ASHRAE Handbook: HVAC Systems and Equipment, Ch. 31 [1], and the VENT II (version 4.1 or more current) computer program, when designing vent systems.

In addition to providing the same requirements as NFPA 54 for vent termination and venting material for different types of combustion appliances, NFPA 211 also provides guidelines for chimney selection based on appliance type and flue gas temperature. Further details regarding required caps for vents and chimneys are also provided. For example, the standard states that caps for chimneys or vents shall be designed to prevent the entry of rain, snow, and birds and other animals. If a vent or chimney cap is not listed (published by an organization that meets code requirements, such as UL 441 Standard [52]), then the minimum distance between the underside of the cap and the top of covered flue must be smaller than the width or depth (whichever is smaller) of the covered flue. If more than one flue is covered, then the smaller dimension of the highest flue shall be used.

The standard also requires that screening material attached to the chimney or vent caps to prevent the entry of animals and insects shall not “adversely affect” the chimney or vent draft. NFPA 211 provides more details regarding masonry chimney design and chimney lining, but references NFPA 54 for properly sizing gas vent systems.

NFPA 90A

NFPA 90A [41] is a standard for the installation of *air-conditioning and ventilating* systems. This standard specifically covers the construction, installation, operation, and maintenance of systems for air conditioning and ventilation, including filters, ducts, and related equipment, to protect life and property from fire, smoke, and gases resulting from fire or from conditions having manifestations similar to fire. NFPA 90A also lists approved materials for fire proofing ventilation systems and preventing flame spread. It does not provide requirements for properly venting combustion appliances.

NFPA 90B

NFPA 90B [42] is a standard for the installation of *warm air heating and air-conditioning* systems. This standard specifically focuses on the construction, installation, operation, and maintenance of systems for warm air heating equipment and air conditioning, including filters, ducts, and related equipment to protect life and property from fire, smoke, and gases resulting from fire or from condition having manifestations similar to fire. NFPA 90B provides detailed instructions for installation of ducts and masonry walls that can also be found in NFPA 211 [40].

ANSI/ASHRAE Standard 62.2-2010

ASHRAE 62.2-2010 [2] is a standard for ventilation and acceptable indoor air quality in low-rise residential buildings. The standard lists minimum requirements for mechanical and natural ventilation systems to prevent backdrafting of naturally vented combustion appliances. This standard, however, does not address specific pollutant concentration levels or potential pollutant sources. The standard also does not address unvented combustion space heaters.

Section 6.4 addresses combustion appliances and states that, "Combustion and solid-fuel burning appliances must be provided with adequate combustion and ventilation air and vented in accordance with manufacturers' installation instructions, NFPA 54/ANSI Z223.1, National Fuel Gas Code, NFPA 31, Standard for the Installation of Oil-Burning Equipment, or NFPA 211, Standard for Chimneys, Fireplaces, Vents, and Solid-Fuel Burning Appliances, or other equivalent code acceptable to the building official. Where atmospherically vented combustion appliances or solid-fuel burning appliances are located inside the pressure boundary, the total net exhaust flow of the two largest exhaust fans (not including a summer cooling fan intended to be operated only when windows or other air inlets are open) shall not exceed 15 cfm/100 ft^2 (75 Lps/100 m^2) of occupiable space when in operation at full capacity. If the designed total net flow exceeds this limit, the net exhaust flow must be reduced by reducing the exhaust flow or providing compensating outdoor airflow. Atmospherically vented combustion appliances do not include direct-vent appliances."

California Residential Code (Title 24, Part 2.5)

The California Residential Code [11] establishes minimum requirements to "safeguard public health". Most of this document is adapted from the International Fuel Gas Code (2009), but incorporates "necessary California amendments". The information specific to combustion appliance venting and spillage/backdrafting is the same as that listed in NFPA 54 [39] and the International Fuel Gas Code [31]. The California Residential code adds the requirement that fireplace walls be a minimum of 4 inches thick. The code requires installation of carbon monoxide alarms in addition to smoke detectors in new dwelling units (see section R315).

California Mechanical Code (Title 24, Part 4)

The California Mechanical Code [9] is based on the 2009 Uniform Mechanical Code [30] and provides complete requirements for the installation and maintenance of heating, ventilating, cooling, and refrigeration systems. This code has the same standards and requirements for combustion air and ventilation as the National Fuel Gas Code [39]. Chapter 7 of the Uniform Mechanical Code specifically addresses combustion air and ventilation.

California Energy Code (Title 24, Part 6)

The California Energy Code [10] describes energy efficiency standards for residential and nonresidential buildings. The purpose of this code is to reduce California's energy consumption. Requirements related to combustion appliances only address insulation for water-heating systems and equipment.

Residential Compliance Manual

The Residential Compliance Manual [12] is intended as an aid to owners, designers, builders, examiners, and energy consultants to comply with and enforce California's energy efficiency standards for low-rise residential buildings. The manual references the California Energy Code (Title 24, Part 6) [10] and ASHRAE Standard 62.2 [2]. With regard to combustion appliances, this manual focuses on defining required appliance energy efficiency. The manual does, however, list the following requirements for combustion appliance venting:

- Combustion and solid-fuel burning appliances must supply combustion and ventilation air from outside according to requirements in ASHRAE Standard 62.2 Section 6.4.
- Combustion appliances must be vented and designed to prevent backdrafting.
- Intermittent ventilation airflow for kitchen range hoods must be a minimum of 100 cfm and intermittent ventilation airflow for the bath fan must be a minimum of 50 cfm (complying with ASHRAE Standard 62.2). However, "care must be taken to avoid backdrafting combustion appliances when large range hoods are used."
- ASHRAE Standard 62.2 includes requirements designed to prevent backdrafting when one or more large exhaust fans are installed within a house containing naturally vented or solid fuel appliances. The requirement states that the net exhaust from the two largest exhaust fans must be less than 15 cfm/100 ft^2 of floor area with either or both fans operating. If the exhaust fans exceed 15 cfm/100 ft^2 of floor area, then an electrically interlocked makeup air fan must be installed. This provision applies only when the naturally vented appliance is inside the pressure boundary of the house, and does not include summer cooling fans designed to operate with the windows open. Direct-vent appliances are not considered naturally vented.
- The ASHRAE 62.2 requirement stated above can be solved by moving all naturally vented combustion appliances outside the pressure boundary of the house, reduce the flow rate of one or more of the fans in the pressure boundary, or install a supply fan to balance the exhaust flow. Enclosed areas outside of the pressure boundary can include a vented garage, attic, or closet. Note: the two largest exhaust fans are commonly the kitchen range hood and the clothes dryer. High-end range hoods can have capacities exceeding 1,000 cfm.

CHAPTER 3: Guidelines and Test Methods for Downdrafting, Backdrafting, and Spillage

Over the past thirty years, test methods for combustion safety have remained essentially unchanged. Current diagnostic methods are broken up into two groups, stress test methods under induced conditions and monitoring under natural conditions [3, 5, 13, 45, 46]. The majority of the tests used on-site for assessing venting performance are stress tests under induced conditions. Further details regarding diagnostic procedures are provided below. Limitations of each test are also given.

Chimney Safety Tests User's Manual

The Chimney Safety Test [14] describes a series of procedures for testing the performance of residential chimney systems. The tests are applicable to all standard houses with conventional heating (using gas, oil, or wood) and ventilation systems. The manual presents five test procedures for identifying houses in which spillage of combustion gases into the living area may occur due to a failure of the chimney venting system. The five tests are briefly described below.

1. The Venting System Pre-Test
   This pre-test, not required but recommended, is a visual inspection of the house to determine if it qualifies for the "more rigorous and time-consuming" Venting System Test. Simple measurements (taking 10 to 15 minutes) are used along with reference tables, containing house depressurization limits, to determine if a house is "venting-safe." The house is depressurized using existing exhaust fans to create a maximum depressurization.

2. The Venting System Test
   This test is designed to ensure that operation of existing household exhaust devices does not adversely affect chimney operation. The impact of fans and fireplace operation on the chimney serving the furnace and/or water heater is tested in addition to the impact of fans and furnace operation on the chimney serving a fireplace. Both the furnace and the fireplace are operated at a maximum level of depressurization to determine if spillage occurs. Spillage lasting more than 30 seconds after the appliance start-up is considered excessive and unacceptable. The test requires 40 to 80 minutes to complete.

3. The Heat Exchanger Leakage Test
   This test provides a quick method for determining if the heat exchanger in an oil or gas forced-air furnace has a major leak. Additionally, the test is a useful diagnostic for determining if the heat exchanger is at fault in a house that experiences spillage. This test is performed after cooling the furnace and then extinguishing the pilot light. Next, exit ports of the combustion chamber are sealed with tape or pieces of foam rubber. Smoke is then placed into the supply air stream (inlet side) of the combustion chamber. Last, while holding the smoke pen near the inlet of the combustion chamber, the circulating blower is turned, pulling the smoke into the combustion chamber. With the circulating blower on, smoke should exhaust out leaks in the combustion chamber, identifying cracks or other leakage areas. Upon completion of the test, the pilot should be relit and the thermostat returned to normal conditions. The guide notes that open flames should not be near the furnace while conducting this test. This test can be completed in 15 minutes.

4. The Chimney Safety Inspection
   This is a visual check for maintenance problems in the chimney system. A checklist is provided as a guide to identify possible repairs and improvements that can improve the performance and

safety of the chimney system. This test can be completed in 20 minutes without special equipment.

5. The Chimney Performance Test
   This test is designed to assess if the chimney is capable of providing adequate draft. The temperature of the gases and pressure in the chimney are measured to determine if condensation is a problem or if the draft is low in the chimney. To conduct this test, a window or door must first be partially opened to the outside. Next, the appliance is operated and a timer is started. Temperature and static pressure inside the chimney are recorded after five minutes of appliance operation. Then the appliance is shut off and the windows and/or doors are returned to their original state. The recorded temperature and static pressure values are compared with listed temperature and house depressurization limits, provided in the manual, to evaluate adequacy of the chimney. This test requires 10 minutes to complete.

CAN/CGSB-51.71-2005: Depressurization Test

The current (2005) CAN/CGSB-51.71 [13] standard is the first revision since its original release in 1995. This standard provides a test method for determining if air-moving devices (i.e., exhaust fans) in a dwelling impair normal venting of combustion appliances. The standard specifically states that the "limits are not suitable for predicting non-heating season performance, such as water heater operation during the summer months." This test method measures worst-case depressurization of a house using existing exhaust fans and compares depressurization measurements to prescribed limits. If the house depressurization exceeds the set limits, it fails the test and the house is considered to have a high potential for spillage. The standard does note that wind can greatly affect the accuracy and repeatability of the test and suggests conducting the test on a calm day. The test also states that it does not guarantee that the listed limits will mean an appliance will always vent properly, as weather can have a significant effect.

CAN/CGSB 51.71 -2005 supersedes CGSB 51.71-95. A few of the differences between the versions are listed below:

- The 1995 version was subtitled "The Spillage Test". The 2005 version is now called "Depressurization Test".
- Pressure-measuring devices were required to measure from 0 to 25 Pa in the 1995 version, but the range is extended to 0 to 50 Pa in the 2005 version.
- The 1995 standard listed "Interior doors on the perimeter rooms not containing exhaust devices should be closed," which was removed in the 2005 version.
- In the pre-test checklist, the 1995 standard stated, "Fuel-fired appliances (furnace, boiler, water heater, gas fireplace, pellet stove) should have the thermostats turned down." The 2005 standard specifies operating conditions for each appliance.
- Air conditioning units were not included in the 1995 standard.
- Continuous pressure limits and intermittent pressure limits were listed separately in the 1995 standard. The 2005 standard groups them together.
- Depressurization limits for the fireplace/wood-burning stove were removed from the 2005 version and a power vent gas appliance depressurization limit was added.

The current test procedure can be summarized as follows. All doors and windows leading outside should be closed. All pressure measuring devices should be calibrated and capable of measuring pressures from 0 to 50 Pa in 1 Pa increments. All exhaust fans and appliances should be turned off (pilot light remaining lit is allowed). Basement doors and doors for an enclosed furnace room should be closed. The test method does not state if other interior doors should be opened or closed to create worst-case depressurization. It only states that doors leading to rooms containing exhaust fans should be tested to create worst-case depressurization in the dwelling space. Each exhaust fan should be operated individually and in combination to depressurize the dwelling. Measurements are taken after each exhaust fan is turned on. The combination of exhaust fans and interior doors open/closed that maximizes the depressurization of the house is the measurement compared to listed values. When wind is present, the standard suggests averaging pressure readings using an electronic manometer with averaging capability or an appropriately sized capillary tube. Depressurization limits for fuel-burning appliances and venting systems are as follows:

Table 1: Depressurization limits for fuel-burning appliances and venting systems from CAN/CGSB-51.71-2005 [13]

Description of Appliance	Max Pressure Limit*
Natural Draft Appliances (includes water heaters, furnaces, and fireplaces)	-5
Sidewall Vented Oil	-5
Pellet Stoves	-15
Sealed Combustion Appliance	-20
Power Vent Gas Appliance	-20

* For infrequently used wood-burning appliances, such as a decorative fireplace, higher depressurization limits may be allowed if they are equipped with warning labels and alarms appropriate for the fuel being burned.

The standard also provides instructions for calibrating pressure measurement devices and suggests taking measurements on a "calm day" to avoid problems associated with wind. A pre-test is available to assess if the dwelling unit requires the depressurization test. It should be noted that this standard does NOT take into account all contributors to depressurization. More specifically, it does not take into account the following:

- Small (<75 L/s) exhaust fans and appliances, such as whole house central vacuum cleaners.
- Powered attic ventilation fans, which may inadvertently draw air from the combustion fuel-burning appliance zone.
- Exhaust caused by a negative pressure in an attached unit of an adjacent dwelling unit, where separation between the units is not complete.
- Exhaust caused by fireplaces or wood stoves.
- Exhaust caused by combustion gas venting from gas or oil-fired appliances, which draw air from the dwelling unit.
- Exhaust caused by windows being left open in closable rooms.
- Stack effect, other than that occurring at the time of test.
- Wind, other than effects occurring at the time of test.
- Operation of central circulating fan at higher speed during cooling.
- Intermittent exhaust during the HRV defrost cycle in cold weather.

ASTM E1998

ASTM E1998 [3] is a guide that summarizes and compares six common procedures for assessing the potential for, or existence of depressurization-induced backdrafting and spillage from vented residential combustion appliances. For each test method, required equipment, test procedures, and technician and testing times are provided. This standard does not include guidelines for fireplaces and stoves. ASTM E1998 also discusses the advantages and uncertainties of each method. Test procedures are grouped into two primary groups: stress tests under induced conditions and continuous tests (minimum one week of monitoring) under natural conditions. Stress tests under induced conditions can only indicate the possibility of backdrafting due to house depressurization. Test methods under natural conditions detect backdrafting/spillage events that occur during normal use of the house during the test.

ASTM E1998 was first released in 1999. In 2002, the standard was revised to include additional research assessing the six test methods. New referenced documents were also added. The standard was revised again in 2007, to include more referenced documents and update the discussion of methods. The current revision (2011) includes an additional scope that states values are in SI units and other minor corrections.

Stress tests under induced conditions are generally less expensive and time consuming, but failure of the stress tests does not indicate how frequently, if ever, an appliance will spill during normal use. The relationship between weather and stress test results also needs further investigation. Continuous tests are capable of isolating actual backdrafting or spillage events and identifying specific operating conditions and weather conditions that lead to backdrafting and spillage. Continuous tests also can provide an indication of the frequency of events if monitoring is conducted over a sufficient period of time (minimum period of one-week is suggested) and can be scheduled to include weather conditions that are most likely to lead to backdrafting.

To assess whether one week is a sufficient period, it is relevant to consider that backdrafting involves a coincidence of several contributing factors that each vary with time. Outdoor temperature, winds, and operation of exhaust fans and air handlers in combination all may contribute to depressurization of the CAZ. The coincidence of these factors with appliance use may occur in a way that leads to backdrafting at a frequency of less than one week, or only during specific weather or seasonal conditions.

The standard also presents a few results from previous researchers, which suggest that backdrafting and spillage events are rare, and stress tests over-classify houses as spillage prone. Additionally, downdrafting events (without appliance operation) may indicate spillage potential, but it is backdrafting events (during appliance operation) that are associated with spillage. Investigating the impact of weather conditions on the results of tests under induced depressurization is also recommended. Listed in Table 2 and Table 3 are a summary of the test methods along with limitations of each test

Table 2: ASTM E1998 [3] summary of stress test methods for assessing the potential for, or existence of backdrafting/spillage from vented residential combustion appliances

Name of Test	Directions	Test Limitations	Estimated Test Time
House depressurization with pre-set criteria	Induce worst-case depressurization with both continuous ventilation and intermittent exhaust. Leave combustion appliances *off*. Measure depressurization, compare to pre-set limits for each appliance type to determine pass/fail for backdrafting and spillage potential.	This test does not assess appliance's ability to overcome house depressurization and does not account for weather variation.	30-40 min
Downdrafting	Induce worst-case depressurization with both continuous ventilation and intermittent exhaust. With combustion appliances *off* (main burners not firing), use lighter or smoke stick to visually check for downdrafting at the draft hood of each naturally vented combustion appliance to determine pass/fail for spillage potential. Record local weather conditions.	This test does not assess appliance's ability to overcome house depressurization and does not account for weather variation. Suggests testing at low wind speeds.	10-20 min + 15-30 min for vent cooling
Appliance Backdrafting	Induce worst-case depressurization with both continuous ventilation and intermittent exhaust. One at a time, *operate* (fire main burner) each naturally vented appliance. Use a lighter or smoke stick to visually check for backdrafting at the draft hood. If appliance does not establish a draft within 5 minutes, it fails the test and has spillage potential. Record local weather conditions.	This test does not account for weather variation. Suggests testing at low wind speeds.	20-30 min
Cold Vent Establishment Pressure (CVEP)	Induce worst-case depressurization with both continuous ventilation and intermittent exhaust. Measure and document worst-case depressurization. Turn off ventilation and exhaust. Use blower door to depressurize house. Fire main burner of appliance being tested and visually monitor spillage and backdrafting. Reduce depressurization until appliance begins drafting. Measure and record the depressurization value at which venting is established. This is the cold vent establishment pressure (CVEP). If the worst-case depressurization exceeds the CVEP, the appliance fails the test (and is deemed a risk for spillage).	This test does not account for weather variation. Suggests testing at low wind speeds.	60-90 min

Table 3: ASTM E1998 [3] summary of continuous test methods for assessing the potential for, or existence of backdrafting/spillage from vented residential combustion appliances

Name of Test	Directions	Test Limitations	Estimated Test Time
Continuous Backdrafting	Monitor and log (using data loggers) the on/off status of main burner for appliance being tested, as well as the vent pressure of that appliance. Document the incidence, duration, and intensity of backdrafting events during monitoring. Minimum duration of one week.	Single week of sampling will capture only limited subset of weather and may miss important coincidences of factors that contribute to depressurization events. Watch for induced draft fans as they can give positive pressures shortly before the furnace fires. Does not measure spillage events.	30-60 minutes + monitoring + 1-2 hours data processing
Continuous Spillage	Monitor and log (using data loggers) the on/off status of main burner for appliance being tested, as well as spillage zone CO and CO_2 concentrations and temperature to determine the incidence, duration, and intensity of spillage events during monitoring. Minimum duration of one week.	Single week of sampling will capture only limited subset of weather and may miss important coincidences of factors that contribute to depressurization events. Spillage temperatures may be misleading due to thermal radiation of appliance.	30-60 minutes + monitoring + 1-2 hours data processing

BPI Technical Standards for the Building Analyst Professional

The Building Performance Institute (BPI) standards for the Building Analyst Professional [5] provide protocols for performing residential energy efficiency and weatherization retrofit work. In particular, this document provides protocols for evaluating building airflow, building heat loss, and combustion safety. Its purpose is to promote a more uniform (and higher quality) application of house performance and weatherization protocols across the workforce. Upon completing a through building analysis, Building Analyst Professionals can provide recommendations for improving performance and maintaining safety of existing houses.

For venting combustion appliances, the BPI document provides three Combustion Safety and Carbon Monoxide Protection protocols. The first protocol is the worst-case depressurization test. This test is conducted by determining the largest CAZ depressurization due to the combined effects of door position, exhaust appliance operation, and air handler fan operation. This test differs from the worst-case depressurization test outlined in ASTM E1998. The test procedure is as follows:

1. Measure the Base Pressure:
   Close all exterior doors, windows, and fireplace damper(s). Set all combustion appliances (boiler, furnace, space-heaters, and water heaters) to pilot setting or turn off the service disconnect. Measure and record the base pressure of the CAZ with respect to outside.

2. Establish Worst Case:
   Turn on the dryer and all exhaust fans. Close interior doors that make the CAZ pressure more negative. Turn on the air handler, if present and leave it on if the pressure in the CAZ becomes more negative, and then recheck the door positions. Measure the net change in pressure from the

CAZ to the outside, correcting for the base pressure. Record the worst-case depressurization and compare to the CAZ Depressurization Limits shown in Table 4.

3. Measure Spillage, Draft, and CO under Natural Conditions:
   If spillage occurs under worst case conditions, turn off the appliance, the exhaust fans, open the interior doors, and allow the vent to cool before re-testing. Test for CO, spillage, and draft under natural conditions (described below). Measure the net change in pressure from the worst case to natural in the CAZ to confirm the worst-case depressurization. Repeat for each appliance, allowing the vent to cool between tests.

Table 4: Building Performance Institute [5] combustion appliance zone depressurization limits for natural draft appliances*

Venting Configuration	Pressure Limit (Pa)
Orphan water heater	-2
Boiler or furnace common vented with a water heater	-3
Boiler or furnace with a vent damper common vented with a water heater	-5
Individual boiler, furnace, or domestic hot water heater	-5
Induced draft boiler or furnace common vented with a water heater	-5
Individual induced draft boiler, furnace, or fan-assisted water heater	-15
Chimney-top draft inducer or direct-vented appliance/sealed combustion appliance	-50

* A clarification report [6] is provided in the next section further explaining terminology and depressurization limits.

The second protocol is the Spillage and Draft Test. This test is to be completed for all natural and induced draft space heating systems and water heaters under worst case depressurization and then repeated for natural conditions if the appliance fails worst-case. If multiple appliances share a chimney, appliances should be tested in order of their burner rating (Btu/hr), starting with the appliance with the lowest Btu/hr rating. Induced draft heating systems are checked for spillage at the base of the chimney liner or flue. If a natural draft and induced draft appliance share a chimney (called a common vent), then spillage should be checked at the water heater draft diverter. For natural draft appliances, vent pressure is also measured under steady-state operating conditions 1 to 2 ft downstream of the appliance draft diverter (draft hood). (Note: some technicians drill a small hole through the inner and outer vent walls to insert a static pressure probe and measure pressure; the hole in each wall must be sealed after tests are completed.) Acceptable minimum draft pressures for specified ranges of outside temperatures are listed in Table 5. If spillage occurs upon startup with a cold chimney, then the time it takes for spillage to stop and a positive draft is established should be documented. Appliances that continue to spill beyond 60 seconds after startup fail the spillage test.

The third protocol is the Carbon Monoxide Test. For this test, a worst-case depressurization test is conducted as described in the first protocol. In this test, CO is measured in the flue of each vented combustion appliance (not in the vent where exhaust gases are diluted). A probe is placed in the flue and measurements are recorded when the appliance reaches a steady-state operating condition. Holes are not to be drilled in flues for power vented or sealed combustion units. All combustion appliances, except for unvented gas cooking appliances, must be tested for CO under worst-case depressurization conditions and normal draft conditions (if the appliance fails under worse-case conditions). Varying retrofit actions are then prescribed based on the CO measurement results, as summarized in Table 6 for vented appliances (does not include gas ovens). If CAZ depressurization limits are exceeded under worst-case conditions, then make-up air must be provided or other modifications may be required to bring depressurization to acceptable limits.

Table 5: Building Performance Institute [5] minimum draft requirements based on outdoor temperature

Outside Temperature (deg F)	Minimum Draft (Pa)
< 10	-2.5
10-90	$(T_{outdoor}/40) - 2.75$
> 90	-0.5

Table 6: Building Performance Institute [5] combustion safety test action levels

Air-free CO in Flue (ppm)	Draft Test Result Requirement	Action
0-25	Pass	Proceed
26-100	Pass	Recommend CO problem be fixed
26-100	Fails at WC only	Recommend a service call to correct problem
100-400*	see Note	Stop Work
> 400	Passes	Stop Work
> 400	Fails either WC or Nat	Emergency: Shut off fuel to appliance and call for immediate service

WC = Worst-case depressurization; Nat = Natural conditions
*Action required if Air-free CO reads 100-400 ppm OR the appliance fails under natural conditions

This BPI standard also provides procedures for testing the safety of range tops and ovens. In this test, all items are removed from the oven interior and then the oven is set to the highest setting. CO is measured in the flue, before dilution air. After 5 minutes of operation, CO measurements are taken. If, at steady state, the oven reads 100 to 300 ppm, then a carbon monoxide detector must be installed. If, at steady state, the oven reads more than 300 ppm, then the unit must be serviced prior to work. If after servicing the oven continues to produce high levels of CO, then exhaust ventilation must be provided with a 25 cfm continuous or 100 cfm intermittent fan.

Inspection of burners on gas stoves, the furnace for flame interference, as well as garage to living space air tightness is also recommended. Analysts are required to carry personal CO monitors during the entire duration of the inspection. If ambient CO levels inside the house exceed 35 ppm, then the analyst is required to abort the inspection.

BPI Clarification of CAZ Depressurization Limits

The BPI Clarification Report [6] (2012) clarifies the definitions and the difference between a stand-alone natural draft water heater and an orphaned natural draft water heater. Additionally, it explains that a -2 Pa CAZ depressurization limit was chosen to ensure that negative pressures within the CAZ do not overcome the negative pressures within the vent. Reportedly, “studies” indicate the need for this specific limit. A natural draft water heater vented into an oversized chimney is treated the same as an “orphaned” appliance connected to a common vent that is no longer connected to a furnace. Oversized chimneys include 6 inches or larger square clay lined chimney (8” is most common), 6 inches or larger round B-vent, or 6 inches or larger round Metalbestos vent. A stand-alone naturally drafted water heater, or a water heater vented into a properly sized chimney, is subject to a -5 Pa depressurization limit.

RESNET Interim Guidelines for Combustion Appliance Testing and Writing Work Scope

This guide [46] is designed for Residential Energy Services Network (RESNET) accredited Raters and Auditors. It provides guidelines for a gas leakage test, worst-case depressurization test, carbon monoxide (CO) test, and a work scope for each test. The gas leakage test is the same as the one outlined in the BPI standard. The worst-case depressurization test is similar to the BPI standard except the RESNET standard requires installation of a blower door to exhaust 300 cfm if a fireplace is present. The purpose of the blower door is to simulate a fireplace in operation. Depressurization limits are listed in the table below. Guidelines for the CO test procedure are similar to the guidelines in the BPI standard. RESNET recommends “if measured CO levels [in the appliance flue] are higher than 100 ppm (200 ppm for an oven) or an appliance fails to meet manufacturer’s specifications for CO production (whichever is higher), the work scope shall specify replacement or repair of the appliance and the house owner shall be notified of the need for service by a qualified technician.”

Table 7: RESNET [46] combustion appliance zone depressurization limits

Appliance Description	CAZ Pressure Limits
Pellet stoves with exhaust fans and sealed vents	-15 Pa
Atmospheric vented oil or gas system (Category I)	-5 Pa
Oil Power Burner (fan-powered, oil burner); fan-assisted or induced-draft gas; solid-fuel-burning appliance other than pellet stove with exhaust fan and sealed vents	- 2 Pa

PG&E Whole House Combustion Appliance Safety Test Procedure

The PG&E Combustion Appliance Safety (CAS) test procedure [45] is intended for use in the Energy Upgrade California program. This test procedure uses similar methods as the BPI Combustion Appliance Safety Procedure [5] and incorporates the Statewide Low Income Program Natural Gas Appliance Testing (NGAT) PG&E Low Income Program Weatherization Installation Standards. All combustion appliances within the living space, including cooking appliances and dryers, are tested to ensure proper drafting. This test procedure recommends inspecting combustion appliance vent caps terminating at the roof or exterior walls of the house for signs of soot (although not stated, one must take appropriate fall protection safety precautions, however, when accessing elevated areas). Minimum CAZ depressurization limits and acceptable draft test ranges are the same as those listed in the BPI standard. Listed in Table 8 are conditions in which a combustion appliance will fail the CAS test.

Carbon monoxide (CO) testing procedures are outlined for water heaters, furnaces and gas cook tops, ranges, ovens, and broilers. Gas dryers do not require CO testing. Test procedures for measuring CO in water heaters and furnaces are the same as those listed in the BPI standard. CO limits for each appliance are shown in Table 9. It should be noted that the CO value for the oven/broiler (226 ppm) may be a typo in the document and should be confirmed by PG&E. For gas cook tops, ranges, ovens, and boilers, the test procedure is as follows:

1. Locate the flue gas termination where applicable.
2. With exhaust fans on, turn on the range burners one at a time, measure and record CO levels 12” above each exposed burner on range tops, cook tops, griddles, and salamanders. Do not expose the sampler tip directly to the flames as false CO readings may occur. A CO level of 26 ppm or

higher means the cooktop(s) fails the CAS test. With all cook top burners operating simultaneously, measure the ambient CO at the center of the kitchen and six feet above the floor after one minute of operation. If CO measurements are 10 ppm or higher, the cook top fails the CAS test. (Note: a measurement made one minute after the start of operation may not allow sufficient time for any CO produced at the cooktop to mix throughout the kitchen).

3. Turn the oven temperature to high, and note the time.

4. Run the oven for a minimum of five minutes making sure the burner stays on. Open the door to prevent oven burner cycling. If a separate broiler burner exists (present in all self-cleaning ovens), test the two burners separately, not at the same time. Find the flue gas termination point and take readings for each oven or broiler burner found on the unit. Record the CO for each burner. CO levels of 226 ppm or higher for ovens or broilers fail the CAS test. Measure the ambient CO for operation of each oven, or broiler burner; ambient CO is measured in the center of the kitchen and six feet above the floor after one minute of operation. If the CO measurement is 10 ppm or higher, then the oven or broiler fails the CAS test.

For gas log fireplaces, a CO measurement is taken at least 12 inches above the flame. A CO reading of 26 ppm or higher means the fireplace fails the test. Ceramic logs must be allowed to heat for at least 10 minutes before the test is conducted. A smoke test must be performed to ensure that the appliance is operating correctly. Continuous spillage also means the fireplace fails the test. Dampers must be open during the test. Gas log lighters do not require CO and draft testing.

Table 8: Conditions, outlined by PG&E [45], in which combustion appliances will fail the Combustion Appliance Safety (CAS) test

Combustion Appliance	Description of Failing Conditions
Water Heater	• Appliance is located within a sleeping area • Appliance is an open combustion water heater with a standing pilot located in the attic with a whole house fan • Contains a soldered flex connector • Appliance is missing BOTH access doors • Components (e.g., draft diverter, vent) are missing. • Gas is leaking near any of the fittings • The vent pipe is damaged, the draft hood is out of alignment, or spillage is occurring • Excessive rust and weak spots due to corrosion • Contains double draft diverters
Gas Heaters	• Contains a soldered flex connector • Appliance is an open combustion water heater with a standing pilot located in the attic with a whole house fan • Appliance is missing flame roll out shield or access door(s) • Components (e.g., draft diverter, vent) are missing. • Gas is leaking near any of the fittings • The vent pipe is damaged or excessive rust and/or weak spots are present due to corrosion
Central Forced Air	• Same criteria as Gas Heaters • Return air ducts are damaged
Gas Cook Tops, Ovens and Broilers	• Gas is leaking near any of the fittings
Gas Dryer	• Gas is leaking near any of the fittings • Dryer is not properly exhausted to outside the building • Dryer exhaust into another gas appliance vent system • Dwelling has a floor furnace and dryer is exhausted under the house

Table 9: Natural gas appliance testing ambient and flue CO action levels for gas service representative calls (Energy Partners Program, 11-05-0)

Appliance/Room	Ambient CO (ppm)	Measurement Location	Air-Free Flue CO (ppm)
Room	10	Center or home 6 ft above floor	N/A
Floor Furnace	2	Above top of unit	101
Forced Air Furnace	2	Inside supply register nearest to furnace	101
Gas Log Heater	2	Above unit	101
Gravity Furnace	2	Inside supply register nearest to furnace	101
Vented Room Heater	2	Above top of unit and draft diverter	101
Wall Furnace	2	Above top of unit and draft diverter	101
Water Heater	10	Above top of unit	101
Range Top[2]	10	Center of kitchen	26[1]
Oven/Broiler	10	Center of kitchen	226[1]
Gas Log Fireplace[2]	N/A	N/A	26[1]

NA = Not Applicable
[1] CO is "as measured" NOT air-free
[2] CO measurements should be taken 12 inches above the flame

Minnesota Mechanical Systems Field Guide

The Minnesota Mechanical Systems Field Guide [37] provides procedures and information for improving the efficiency of residential heating and cooling systems. This guide provides test procedures for measuring draft in combustion appliances. Test procedures include 1) the smoke test, where the appliance is turned on and a smoke stick or match is used to determine if the appliance is venting properly, and 2) the worst-case draft and pressure test, where pressure inside the vent of the combustion appliance is monitored while exhaust fans are operated and interior doors are open and closed. If the pressure in the vent reaches zero or goes positive, then the appliance is assumed to have a problem. Listed in Table 10 are draft problem solutions. This guide also provides minimum worst-case draft for given outdoor temperatures (see Table 11). The document also provides guidelines for venting material, sizing, and termination and follows the same criteria stated in NFPA 211 [40].

Table 10: Natural daft problems and solutions
(From Table 3-1 in the Minnesota Mechanical Systems Field Guide [37])

Problem	Possible Solution
Draft never established	- Check for chimney blockage - Seal chimney air leaks - Provide additional combustion air
Blower activation weakens draft	- Seal leaks in furnace and return ducts - Isolate furnace from return registers
Exhaust fan weakens draft	Provide make-up combustion air if opening outside door or window strengthens draft
Closing interior doors during blower door operation weakens draft	Add one of the following: - Return ducts - Grills between rooms - Jumper ducts

Table 11: Natural minimum worst-case draft
(From Table 3-2 in the Minnesota Mechanical Systems Field Guide [37])

Appliance	Outdoor Temperature (deg F)				
	< 20	**21-40**	**41-60**	**61-80**	**> 80**
Gas fired furnace, boiler, or water heater	-5 Pa	-4 Pa	-3 Pa	-2 Pa	-1 Pa
Oil-fired furnace, boiler, or water heater	-15 Pa	-13 Pa	-11 Pa	-9 Pa	-7 Pa

CHAPTER 4:
Prior Research Assessing Codes, Standards, and Guidelines

Extensive research has been conducted in the United States and in Canada to assess the codes, standards, and guidelines in Chapter 3. Much of the literature prior to 1998 [8, 22, 32, 36, 43, 51] assisted in developing ASTM E1998 [3]. Since 1998, research has focused primarily on assessing the repeatability and reliability of standards and guidelines [7, 23, 33, 34, 35, 44]. In particular, research conducted after 1998 broadly has concluded that stress-induced tests are not reliable indicators of spillage potential and are too conservative when predicting spillage (i.e., they predict more spillage than actually occurs). Additionally, the tests do not adequately address water heaters, which are more likely to spill than furnaces (water heaters are more prone to spill in warmer weather). This tendency occurs because the buoyant force that drives airflow is proportional to the temperature difference between the vent gases in the chimney column and the outdoor air. When outdoor air is warmer, the temperature difference and the buoyant force are both reduced. Water heaters are more sensitive to this effect because they generally have smaller burners and thus produce a lower heat flux in their exhaust gases. Also contributing is the reverse stack effect: when indoor temperatures are lower than outdoors, the direction of airflow across the upper building envelope is inward.

For monitoring, researchers have suggested collecting data over longer periods of time to increase test accuracy [23, 35]. Research has also suggested that a house should not be considered as spillage-prone unless it has failed multiple stress-induced tests [23]. Most of the published literature states that continuous tests are more indicative of spillage events than stress-induced tests and if continuous tests are taken for longer periods of time, can better capture effects of weather. In general, houses that met venting design criteria set by the National Fuel Gas Code [39] yield systems with a high probability of venting properly [7].

A summary of the research assessing codes, standards, and guidelines for combustion safety is provided below. This review builds upon a prior review, which focused on literature relevant to residential mechanical system commissioning [55].

Flame roll-out study for gas fired water heaters (1988)

Kao et al. [32] tested five gas-fired water heaters (four natural gas and one liquid propane) in a laboratory with simulated house conditions to evaluate their flame roll-out (flames escaping from the lower part of a water heater) characteristics. They tested the effects of flue blockage, space pressure depressurization, and access door status on flame roll-out. Flame roll-out was identified when temperatures outside the jacket or in the lower part of the water heater exceeded 270°F.

Test results were compared to results from a proposed ANSI test method for testing water heater performance and safety. The authors found that flue blockage, depressurization, and access door status (open/closed) are all major factors in inducing flame roll-out. In conclusion, they made the following recommendations to the U.S. Consumer Product Safety Commission (CPSC) and the ANSI subcommittee on water heaters:

- The final ANSI test method should add a temperature criterion for determining flame roll-out.
- The final ANSI test method should require an interlocking device for access doors to ensure the access door remains closed during heater operation. Additionally, a test method for proper operation of the interlocking device should be included.

- Flue designs should be improved to prevent flow reversal, which causes flame roll out under depressurized conditions.
- Thermal devices should be added to the outside of the water heater and automatically shut off the appliance when temperatures exceed 250°F, indicating flame roll-out.

Chimney Venting Performance Study (1988)

Timusk et al. [51] investigated spillage and backdrafting of 40 houses in the Metropolitan Toronto area by conducting the Cold Vent Establishment Pressure (CVEP) test and the Hot Vent Reversal Pressure (HVRP) test. The HVRP test is similar to the CVEP test, but the appliance is operating and establishes venting before the blower door is used to depressurize the house and reverse the already established upward draft. All houses selected for testing had naturally aspirating gas furnaces and preference was given to houses containing fireplaces (24 of 40 houses). Of the forty houses tested, 36 houses had gas water heaters, which were common vented with the furnace. Wind conditions and outdoor temperatures were measured prior to conducting backdrafting tests. Maximum house depressurization from fireplaces was measured using a "roaring fire" in the fireplace. Maximum house depressurization from exhaust fans was measured when all exhaust fans were operating with all interior doors open. CVEP was measured during furnace operation, water heater operation, and when both appliances were operating simultaneously. The average tightness of the houses tested was 6.4 ACH50 (3.1 ACH50 for the tightest house).

As shown in Fig. 1, the average CVEP measured was 6 Pa, while the lowest CVEP measured was 2 to 3 Pa. Of the forty houses tested, eleven had maximum depressurizations greater than 5 Pa, (see Fig. 2). For each house, the fireplace accounted for at least half of the depressurization. Figure 3 shows distributions for CVEP, HVRP, and house depressurization due to exhaust fans and fireplaces. The distributions were approximated using a normal distribution with the population mean approximated by the sample mean and the population standard deviation approximated by the sample standard deviation. Their results show that the probability of exhaust fan measurements, without the fireplace, exceeding furnace CVEP measurements is about 3% and about 0.03% for HVRP measurements. Houses with fireplaces were shown to have a higher probability (23%) of depressurizing the house beyond the CVEP limit, as shown in Fig. 4(c).

The authors concluded that appliances were able to establish venting in downdrafting chimneys over a range of wind speeds and outdoor temperatures. They found no visible correlation between outdoor temperature and CVEP or wind speed and CVEP. However, results showed that windy conditions assisted in venting combustion appliances. Venting in shorter, one-story, houses was not as reliable as venting in taller, three-story, houses (presumably because of a reduced buoyant force from a shorter column of air in the chimney). Additionally, venting in external chimneys was not as reliable as venting through chimneys that rise within the building envelope (presumably because of a reduced buoyant force from a cooler column of air in the chimney). Techniques developed in this study led to many protocols for the Cold Vent Establishment Pressure test published in the ASTM E1998 [3].

Figure 1: Distribution of CVEP for furnaces, water heaters, and furnaces and water heaters operating simultaneously. Data were taken from 40 houses located in Toronto (1988) [51].

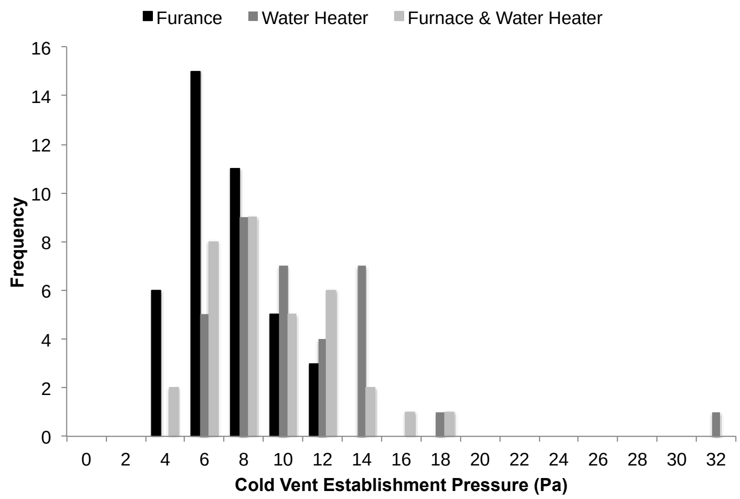


Figure 2: Distribution of total house depressurization from operation of exhaust-fans and fireplace. Data were taken from 40 houses located in Toronto (1988) [51].

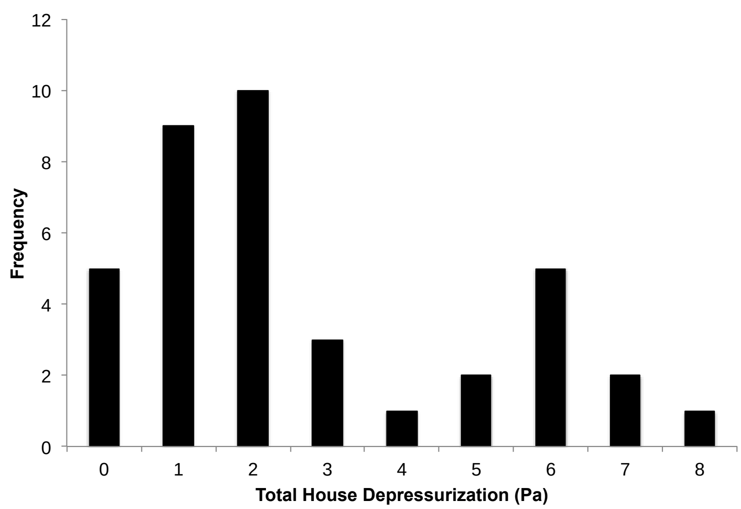
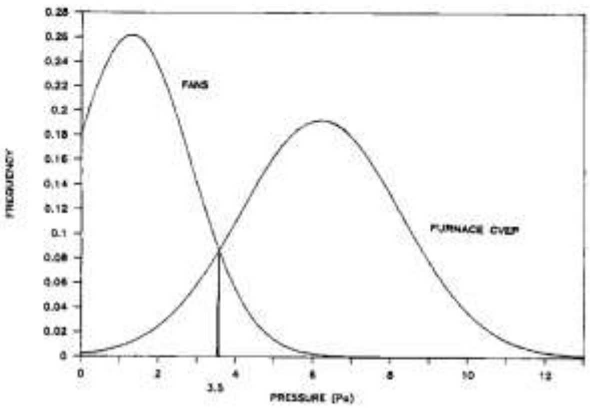
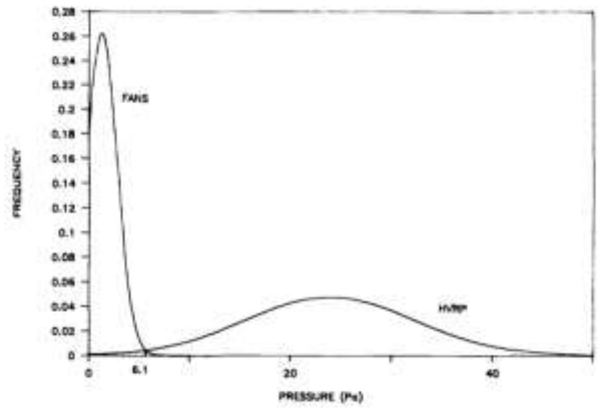


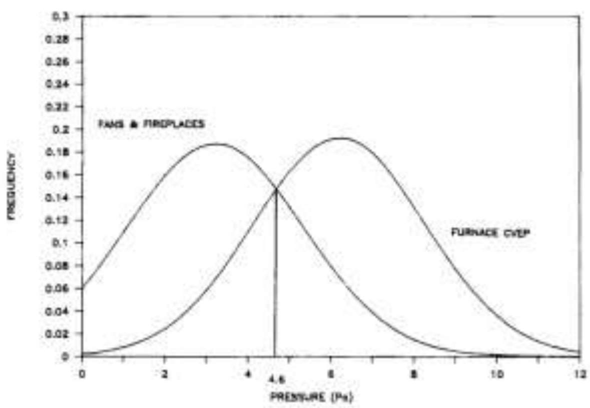
Figure 3: Normal distributions of furnace CVEP and HVRP tests versus house depressurization from fans and fireplaces. Data were taken from 40 houses located in Toronto (1988) [51].



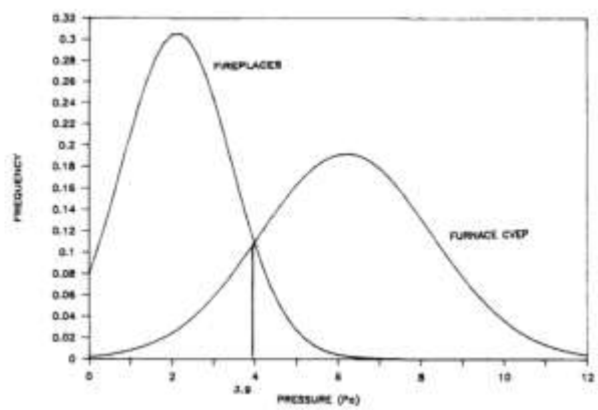
(a) Distribution of furnace CVEP and house depressurization from operating exhaust fans. Mean depressurization from fans = 1.32 Pa, standard deviation = 1.49 Pa, mean furnace CVEP = 6.2 Pa, standard deviation = 2.08 Pa. Probability of one random reading being under both normal curves simultaneously = 3%



(b) Distribution of furnace HVRP and house depressurization from operating exhaust fans. Mean depressurization from fans = 1.84 Pa, standard deviation = 1.49 Pa, mean furnace HVRP = 23. 9 Pa, standard deviation = 8.37 Pa. Probability of one random reading being under both normal curves simultaneously = 0.03%.



(c) Distribution of furnace CVEP and house depressurization from operating exhaust fans and fireplace. Mean depressurization from fans and fireplace = 3.16 Pa, standard deviation = 2.08 Pa, mean furnace CVEP = 6.2 Pa, standard deviation = 2.08 Pa. Probability of one random reading being under both normal curves simultaneously = 23%.



(d) Distribution of furnace CVEP and house depressurization from fireplace operation. Mean depressurization from fireplace = 2.01 Pa, standard deviation = 1.28 Pa, mean furnace CVEP = 6.2 Pa, standard deviation = 2.08 Pa. Probability of one random reading being under both normal curves simultaneously = 3%.

Combustion Safety Checks: How Not to Kill Your Clients (1995)

In this article, which was written for contractors, inspectors, and energy auditors, deKieffer [17] discusses the risk of carbon monoxide (CO), the mechanism of incomplete combustion in naturally vented combustion appliances, and the release of CO as part of the exhaust mixture. Overall, the article presents a general, qualitative list of safety categories to consider when testing combustion appliances. It also offers advice for organizations wanting to establish their own combustion safety testing standards.

Understanding Ventilation: How to Design, Select, and Install Residential Ventilation Systems (1995)

In this book, Bower [8] provides an overview of concerns about and causes of backdrafting and spillage. The author states that backdrafting and spillage are results of house depressurization and combustion appliance venting design. The author also provides suggestions for decreasing the risk of spillage and how to evaluate spillage. The procedure described by the author mimics the worst-case depressurization test outlined in the ASTM E1998 [3]. He also states that the differential pressure in the vent is dependent on the temperature stack effect. Overall, the book provides a good resource for explaining causes of backdrafting and spillage as well as methods for decreasing spillage hazards in houses.

Residential Depressurization Protocol Development and Field Study (1995)

Grimsrud et al. [22] developed a working protocol to measure the impact of depressurization on backdrafting and spillage of vented gas combustion appliances. They tested the protocol on nine Minnesota houses and one Chicago house, the GRI Research House, during winter weather conditions. All houses had atmospherically vented furnaces and nine houses had natural draft water heaters common vented with the furnace. One house had a fan assisted furnace common vented with a natural draft water heater. Nine houses had two stories and one house, the GRI Research House, was a single story. All combustion appliances were located in the basement of the house. A summary of house characteristics can be found in Table 12.

The protocol includes a stress test and one week of monitoring of combustion appliances for backdrafting and spillage. The stress test included three major procedures: First, worst-case depressurization in the CAZ was measured by turning on all the exhaust appliances located in the home and leaving all interior doors open. Second, CO in the flue of the appliance was measured in one-minute intervals for five minutes during worst-case depressurization. The author did not state if the reported CO measurements are on an air-free basis. Pressure at the base of the vent was also recorded and used as an indicator for backdrafting. Ambient CO_2 and CO were measured in the CAZ during the duration of the test. Third, if the appliance did not exhibit spillage during the previous test, then a blower door was used to determine depressurization levels leading to spillage, mimicking the CVEP test [3]. Flue CO measurements were also recorded every minute for five minutes during backdrafting induced by the blower door.

For monitoring, CO measurements in the CAZ and differential pressure between the vent and the CAZ were used to indicate backdrafting or spillage. Monitoring was used to verify predictions of the stress test. Figure 4 shows the location of the house measurements and measurements recorded. Differential pressure between the CAZ and outdoors (Channel 1) was recorded along with differential pressure between the windward and the leeward side of the house (Channel 2). Exhaust fan appliance status and combustion appliance status was also recorded using temperature and pressure sensors. Indoor air quality was assessed by monitoring CO_2 on each level of the house and measuring ambient CO near other possible sources, such as a gas cooktop in a kitchen or the garage attached to the house. Indoor and outdoor temperatures were also recorded.

Results from the stress test, including outdoor temperature and baseline pressure, are shown in Table 13. Draft columns in Table 13 indicate if the appliance was drafting. A "no" indicates that the appliance spilled during the entire test. A time period indicates the duration after start-up during which the appliance spilled before draft was established. The authors noted that house MI1 had dirty boilers, which could have caused the high CO measurements. Stress tests indicated that four of the ten homes (EP2, EP1, WO1, and AV1) had evidence of backdrafting or spillage in at least one gas appliance.

One-week of monitoring showed sustained backdrafting events (greater than 1 hr) in three homes (EP2, WO1, and AV1) and high CO levels in one home (AV1). Table 14 shows a summary of the one-week test results. Although the stress test predicted house EP1 having backdrafting problems, the one-week of monitoring showed no evidence of spillage. House EP2 was recorded having three major backdrafting events. The first event lasted 3 hours, the second event lasted 9.5 hours, and the third event lasted 10 hours. House WO1 also had three major backdrafting events, all of which were triggered by the fireplace. House AV1 had the longest duration of backdrafting (12 hrs) and had the highest measured CO in the CAZ and the furnace. Table 15 provides a summary of sustained backdrafting events from houses EP2, WO1, and AV1.

The authors concluded that combustion backdrafting and spillage is a pressure problem. The results showed stable, long-term backdrafting in three of the ten houses tested and backdrafting events persisted even after the triggering event was removed. Elevated levels of CO_2 and water were released during the extended spillage, but carbon monoxide production was minimal in all but one house.

Table 12: House characteristics from homes located in Minnesota and Chicago (1995) [22]

House	Year Built	Area (sq. Ft)	Stories	Furnaces	Water Heaters	CFM 50 (CFM)	ACH 50 (1/hr)
ED1	1952	2460	2	1	1	2440	9.1
EA1	1993	2400	2	1	1	1280	3.3
MI1	1921	5400	2	2 (B)	2	4190	5.8
EP2	1993	3100	2	1	1	1560	3.4
EP1	1993	4750	2	1 (ID)	1	1960	3.1
WO1	1993	3900	2	1	1	1620	2.9
AV1	1994	4900	2	1	1 (E)	1580	2.2
OR1	1992	5250	2	2	1	3860	5.1
WO2	1994	3175	2	1	1	2300	5
CH1	1957	2300	1	1 (ID)	1	3860	12.5

ID – Induced Draft; B – Boiler; E – Electric

Figure 4: Grimsrud et al. [22] house measurements and measurement locations for homes in Minnesota and Chicago

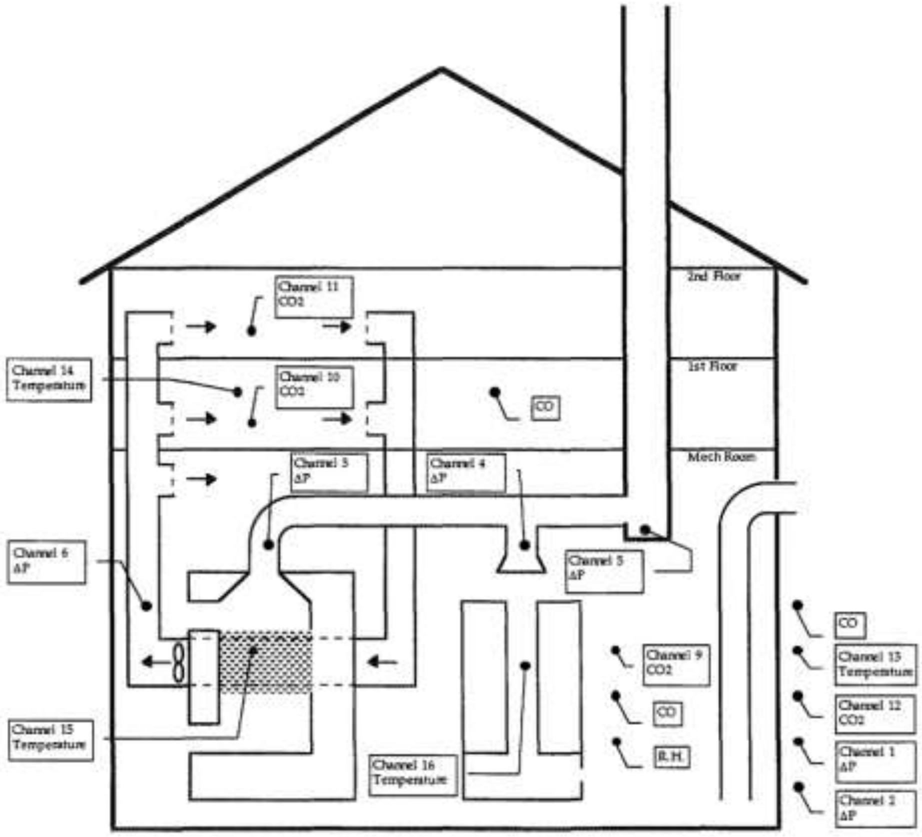


Table 13: Stress test results from homes located in Minnesota and Chicago (1995) [22]

House	Outdoor Temp (°F)	Baseline Pressure (Pa)	Worst-Case Depressurization (Pa)	Water Heater		Furnace	
				Max Flue CO (ppm)	Draft	Max Flue CO (ppm)	Draft
ED1	15	-4.1	-6.9	5	Y	11	Y
EA1	20	-4	-8.3	130	Y	22	Y
MI1	32	-4	-6.4	<20/ <50	Y/Y	2000/770	Y/Y
EP2	25	-2.2	-7.5	2	N	20	90 sec.
EP1	27	-2.1	-8.9	495	4 min	57	Y
WO1	29	-5.6	-26	26	N	130	N
AV1	45	-2	-9.5	NA	NA	>2000	N
OR1	14	-4.4	-11.3	28	Y	23/29	Y/Y
WO2	23	-5.5	-9.7	4	Y	6	Y
CH1	24	-1.4	-2.9	20	Y	35	Y (fan assist)

Table 14: One-week, monitoring test results from homes located in Minnesota and Chicago (1995) [22]

House	Extended Backdrafts	Max CAZ CO (ppm)	Max CO source	Max CAZ CO_2 (ppm)
ED1	None	17	Car Port	940
EA1	None	8	Garage	900
MI1	None	5	Boiler 2	1700
EP2	3	18	Garage	2500
EP1	None	5	Garage	800
WO1	3	11	Garage	2700
AV1	1	> 1000	Furnace	>3000**
OR1	None	near 0	N/A	600
WO2	None	near 0	N/A	800
CH1*	None	> 50	(indep. Source)	2900

*Artificial introduction of CO and CO_2 using CO source and blower door to induce reverse flow
**3000 ppm is the upper-limit of the CO_2 monitors

Table 15: Detailed one-week, monitoring test results from homes with extended backdrafting events located in Minnesota (1995) [22]

House	Sustained Backdrafting Event	Trigger of Backdrafting	Duration (hrs)	Max CAZ CO from appliance (ppm)	Max CAZ CO_2 from appliance (ppm)
EP2	1	Unknown	3	near 0	> 2000
	2	Unknown	9.5	NA	NA
	3	Fireplace	10	NA	NA
WO1	1	Fireplace	3	near 0	2700
	2	Fireplace	4	near 0	2100
	3	Fireplace	4.3	near 0	2500
AV1	1	Range fan, Dryer, and Fireplace	> 12	> 1000	> 2000

The Effect of House Depressurization on the Operation of Gas Appliances (1996)

Aronov et al. [4] investigated the effects of house tightening and house depressurization on the operation of vented gas appliances. All tests were conducted on the American Gas Association (AGA) Research House. The AGA Research House is a 2480 ft^2 two-story house, with a basement. The house had two bathroom exhaust fans rated at 85 cfm and 120 cfm, and a range hood rated at 200 cfm. Gas appliances (furnaces and water heater) were located in the basement and vented through a 12 inch by 12 inch masonry chimney or a Type B vent, depending on the experiment. Three different types of furnaces were investigated: a fan-assisted furnace with differential pressure proof of flow switch, a fan-assisted furnace with spillage sensor, and a draft hood-equipped furnace with combustion air damper. Two types of water heaters were tested: a draft hood (natural draft) water heater and a water heater with an aftermarket induced draft fan that included a spillage detector mounted around the draft hood. The tightness of the house was around 0.2 ACH at 5 Pa, but could be adjusted by opening or closing ports.

Combustion spillage was measured by injecting a tracer gas, SF_6, into the exhaust stream near the end of the combustion system before the induced draft fan. The amount of tracer gas measured in the living space indicated the amount of spillage from the combustion appliance. For each experiment, tracer gas was only injected into the exhaust stream when the appliance was operating. Tracer gas was sampled in several rooms in the house, including the basement, and in the cold air return ducts. The tracer gas spillage method was validated by inducing 100% spillage and taking samples.

In addition to identifying combustion spillage, backdrafting was indicated using thermocouples installed in the water heater vent connector near the draft hood. Differential pressures throughout the house and across the building envelope were also measured. Temperature measurements were taken in each room of the house, in the basement, and outside the house.

When comparing ACH, depressurization, and building tightness, their results showed that the more the house is depressurized, the higher the ACH rate; however, the leakier the house, the greater the ACH rate for the same level of house depressurization. Their results also showed more air exhausted from the house led to more depressurization, as expected.

To investigate the effects of depressurization on spillage, the authors introduced the “effective depressurization” as a means of normalizing depressurization data and including effects of outside temperature. The effective depressurization is defined as,

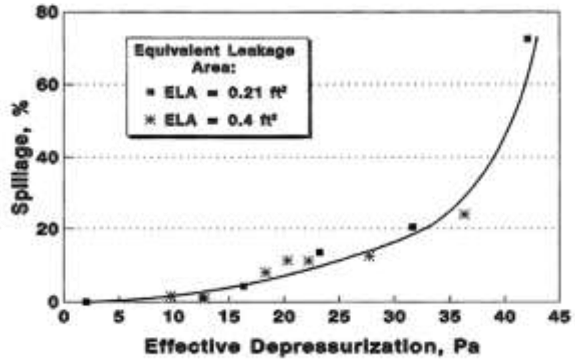
$$\Delta \mathrm{dp_{eff}} = \Delta \mathrm{P_{dp}} + \left(1 - \frac{\mathrm{T_{air,ref}}}{\mathrm{T_{air}}}\right) \mathrm{h} \cdot \mathrm{g}, \quad (1)$$

where $\Delta \mathrm{dp_{eff}}$ is the house depressurization (differential pressure between indoors and outdoors) in Pa, $\mathrm{T_{air,ref}}$ is the reference outside air temperature in Kelvin, $\mathrm{T_{air}}$ is the outside air temperature in Kelvin, h is the stack height in meters, and g is gravitational acceleration (9.8 m/s^2). The effective depressurization was used in all correlations with spillage, while ACH rate was correlated with pressure drop across the house envelope.

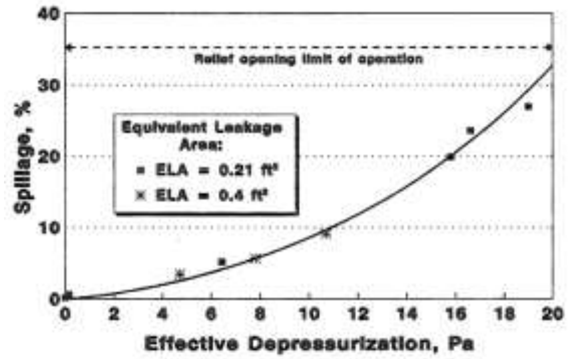
Experimental results showed that spillage is a function of depressurization and is not directly affected by the effective leakage area. Figures 5(a) and 5(b) show a power-law correlation between spillage and effective depressurization for the induced draft furnaces vented alone. For induced draft furnaces common vented with the water heater and for the natural draft furnace vented alone, the power-law correlation only applied to initial depressurization. Then spillage followed a sharp transition to 100% spillage, as shown in Figures 5(c) and 5(d). These correlations were independent of venting system material; however the masonry chimney transitioned to 100% spillage at effective depressurizations around 8 to 9 Pa while the Type B vent transitioned around 13 to 14 Pa (see Fig. 6(d)). The natural draft water heater and the induced draft water heater followed the same trends as the natural draft furnace and the induced draft furnace.

The authors conclude that spillage depends on depressurization and is not directly affected by the effective leakage area. For fan assisted appliances and water heaters vented alone, a power-law correlation can be used to relate spillage and effective depressurization. For fan assisted furnaces common vented with a water heater or for natural draft appliances (water heaters and furnaces), spillage initially follows a power-law correlation with effective depressurization, but quickly transitions to 100% spillage as effective depressurization increases. The location of the transition zone depends on the venting system being used. The authors recommend conducting a full field survey to further identify performance patterns.

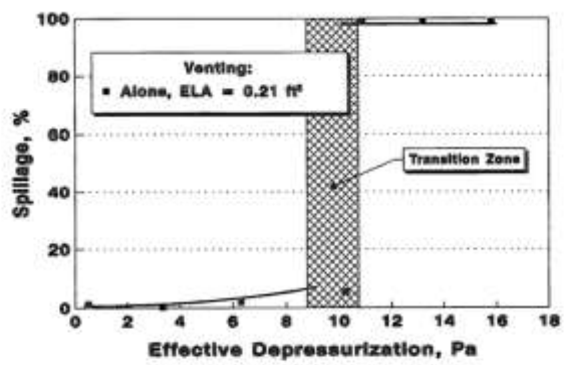
Figure 5: Correlations between spillage and effective depressurization for induced draft and natural draft combustion appliances tested in AGA Research House (1996) [4]



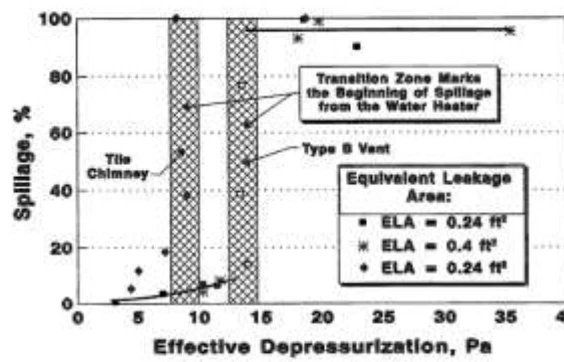
(a) A power-law correlation is shown between spillage and effective depressurization for the induced draft furnace with a pressure switch vented alone using a Type B vent. Spillage came from the vent connector and was not affected by the effective leakage area.



(b) A power-law correlation is shown between spillage and effective depressurization for the induced draft furnace with a relief opening vented alone using a Type B vent. Spillage came from the relief and vent connector and was not affected by the effective leakage area.



(c) For the natural draft furnace vented alone using a Type B vent, a power-law correlation is shown initially between spillage and effective depressurization followed by a transition zone and then 100% spillage regardless of effective depressurization. The transition zone marks an abrupt change to backdrafting.



(d) For the induced draft furnace with pressure switch common vented with a water heater using a Type B vent and tile chimney, a power-law correlation is shown initially between spillage and effective depressurization followed by a transition zone and then 100% spillage.

Protocols for Assessing Pressure-Induced Spillage from Gas-Fired Furnaces and Water Heaters (1996)

Koontz et al. [36] initiated a pilot study to develop, test, and refine protocols for assessing pressure-induced spillage from gas-fired furnaces and water heaters. Two main protocols they developed and tested determine spillage potential using a “one-time” (stress) measurement and actual occurrences using monitoring over seven or more days. In this study, protocols were developed from data collected in four stages: 1) House selection and recruitment, 2) initial technician survey, 3) detailed technician investigation, and 4) unattended monitoring. Table 16 provides a summary of the data collection stages and information collected during each stage.

In the first stage of data collection, House Selection and Recruitment, 108 houses in Washington, DC were surveyed. Of the 108 houses, 20 houses were selected to complete the Initial Technician Survey along with the Gas Research Institute's (GRI) research house located in Chicago, IL (21 houses in total). Six of the houses that completed the Initial Technician Survey (including the GRI research house) were chosen for the Detailed Technician Investigation and tested for backdrafting potential using the stress test methods.

The six houses in the Detailed Technician Investigation were also tested using the Unattended Continuous Monitoring (UCM) for a minimum of one week (7 days). The following measurements were recorded during the UCM: appliance ON/OFF status, fireplace ON/OFF status, temperature in the spillage zone, temperature in two locations in the vent connector, temperature in the common vent, outdoor temperature, temperature in the CAZ, temperature near the thermostat, temperature in the heat exchanger of the appliance, CO in the spillage zone, CO_2 in the spillage zone, CO_2 in the CAZ, relative humidity in the spillage zone, voltage indicating exhaust fan status, NO in the spillage zone (Furnace only), NO_2 in the CAZ, temperature indicating dryer status, differential pressure between the CAZ and outdoors, differential pressure between the common vent and the mechanical room, and static pressure in the vent connector vs. the CAZ.

The results from the stress tests indicated that House 1 had potential for pressure-induced spillage. Both the water heater and the furnace CVEP (3 Pa and 4 Pa, respectively) were below or equal to the measured worst-case depressurization (4 Pa). Table 17 provides a summary of the stress tests for all six houses.

During the one-week of monitoring, House 1 showed spillage events from the water heater and the furnace; however, the spillage events only lasted for 1 to 2 minutes during start-up and coincided with dryer or exhaust fan operation. After 2 minutes of start-up, each appliance vented normally. House 500, the GRI research house, showed spillage during start-up of both appliances, but the authors purposely depressurized the house, causing the appliances to spill. The authors reported emissions measurements for only three of the six houses (including the GRI research house). Tables 18 and 19 provide a summary of emissions measurements in the spillage zone and CAZ, respectively.

The authors concluded that tight houses with high potential to depressurize the house with existing exhaust fans have more spillage potential. However, actual spillage events measured using Unattended Monitoring occurred only during appliance start-up (1 to 2 min) and were rare. Their results show that the most reliable predictor of spillage potential is the ratio of depressurization capability, using continuous and intermittent exhaust fans, to the CVEP, but further investigation is required. For the monitoring, the authors note that temperature alone is not sufficient for indicating actual spillage events and NO and NO_2 readings could be removed from the protocol.

Table 16: Koontz et al. (1996) [36] summary of data collection stages and durations for houses in Washington, DC

Data Collection Stage (duration)	Information Collected
House Selection and Recruitment (5-15 minutes for screening questionnaire)	• House type and age • House tightness indicators • Furnace and water heater fuel, age location and condition • Other combustion appliances • Exhaust appliances
Initial Technician Survey (1-2 hours)	• General dimensions/layout of house • Furnace and water heater fuel, capacity and age/condition • Chimney/flue characteristics • Depressurization measurements • Simple backdraft/spillage test (smoke pencil)
Detailed Technician Investigation (3-4 hours)	• House tightness (blower door) • House depressurization potential (exhaust fans) • Neutral pressure level (base pressure) • Cold Vent Establishment Pressure (CVEP) • Hot vent reversal pressure (HVRP)*
Unattended Monitoring (6-8 hours for installation, 7+ days for monitoring)	• Furnace and water heater temperatures • Vent and chimney temperatures • House depressurization • Vent and chimney static pressures • Spillage-zone temperatures, relative humidity, and combustion products (CO, CO_2, NO_x) • Status of combustion and exhaust appliances

* The hot vent reversal pressure, or HVRP, refers to the level of house depressurization at which a normally venting combustion appliance starts to backdraft (similar to the CVEP test, but the appliance is operating and establishes venting before the blower door is used to depressurize the house and reverse the already established upward draft).

Table 17: Koontz et al. (1996) [36] summary of stress test results from houses in Washington, DC

House ID	ACH 50 (Pa)	Worst-case depressurization (Pa)	Furnace CVEP (Pa)	Furnace HVRP (Pa)	Water Heater CVEP (Pa)
1	8.9	4.0	4.0	14.0	3.0
16	9.1	3.5	5.0	29.0	3.0
22	11.9	4.4	7.5	15.0	NA
23	8.3	2.3	20.0	27.5	7.5
313	8.2	3.6	9.4	23.0	4.3
500	8.0	2.1	4.0	15.0	3.0

Table 18: Summary of maximum spillage zone emissions measurements during one-week monitoring from GRI Research House and selected houses in Washington, DC (1996) [36]

House ID	Appliance	Max CO in spillage zone (ppm)	Duration of Max CO (min)	Max CO_2 in spillage zone (ppm)	Duration of Max CO_2 (min)	Max NO in spillage zone (ppm)
1	Furnace	25	1-2	700	1-2	0.55
	Water Heater	19	1-2	2500	1-2	-
16	Furnace	<1	-	600	15	<0.1
	Water Heater	<1	-	450	60	-
500 (GRI House)	Furnace	45	30	2750	5	15
	Water Heater	45	30	750	1-2	-

Table 19: Summary of maximum emissions measurements in CAZ during one-week monitoring from GRI Research House and selected houses in Washington, DC (1996) [36]

House ID	Max CO_2 in CAZ (ppm)	Max NO_2 in CAZ (ppm)
1	500	<0.1
16	NA	<0.1
500 (GRI House)	NA	0.2

Field Protocol for Determining Depressurization-Induced Backdrafting and Spillage from Vented Residential Gas Appliances (1996)

In this report, Grimsrud et al. [25] combined two prior GRI-sponsored pilot studies [22, 36] to develop a common protocol for determining backdrafting and spillage potential in gas appliances. This report provides the field protocol and describes step-by-step procedures for characterizing houses, installing equipment for stress tests and monitoring, measuring house tightness and depressurization levels, and testing backdrafting and spillage potential due to depressurization. The entire protocol can be completed in 4 to 6 hours. No houses were tested in this report. Only a protocol for testing is provided. Table 20 provides a summary of the test methods.

Table 20: Grimsrud et al. (1996) [25] summary of Test Procedures Determining Depressurization-Induced Backdrafting and Spillage

Test Method	Summary of Procedures
Appliance Qualification and Efficiency	• Measure ambient CO and CO_2 • Measure combustion products in the flue (CO and CO_2) • Measure efficiency of combustion appliance(s)
Site Characterization	• Sketch house exterior and floor plan • Take inventory of appliances • Characterize venting system for water heater and furnace
Installation of Measurement Equipment	• Install laptop computer, data acquisition box, and sensors for pressure, temperature, and combustion products • Set system to collect data with 5 second averages during stress tests
House Tightness	• Record local weather conditions • Close all doors and windows • Conduct Blower Door test to measure tightness
House Depressurization Level and Backdrafting	• Close all doors and windows to outside • Sequentially turn on exhaust equipment and open and close interior doors to achieve maximum depressurization (like BPI test [5]) • Use smoke pencil to assess backdrafting
Cold Vent Establishment Pressure (CVEP)	• Use a blower door to substantially depressurize the house • Start appliance • Gradually lower house depressurization until appliance establishes draft • Record depressurization value when draft is established

Causes and Consequences of Backdrafting of Vented Gas Appliances (1996)

This article, written by Nagda et al. [43], provides a brief review of previous studies investigating depressurization-induced backdrafting and spillage from natural draft combustion appliances. The studies were conducted in Canada, Europe, and the United States. The literature showed that the mean depressurization of houses ranged from -3.0 to -7.6 Pa while the mean CVEP ranged from -6.2 to -9.7 Pa. The mean house tightness was not provided in the article. Many of the studies showed one third of the houses tested had backdrafting problems, but CO measurements were always less than 7 ppm in the living space. In many instances, CO measurements inside the house were lower than CO measurements outside and higher measurements of CO indoors were often caused by unvented appliances or poor burner tune.

The article concludes that causes for house depressurization are well understood, but the frequency and consequences of depressurization-induced spillage are poorly understood, despite the considerable amount of research that has been conducted. The author recommends that future research clearly define the potential problem with naturally vented combustion appliances and that codes and standards be developed to address the problem.

Initial Surveys on Depressurization-Induced Backdrafting and Spillage: Volume I - Washington, DC and Omaha, NE (1999)

Koontz et al. [35] conducted initial surveys in Washington, DC and Omaha, NE to assess the robustness of test procedures outlined in the ASTM E1998 [3]. Four stress tests were conducted: 1) House depressurization test with pre-set criteria, 2) Downdrafting test, 3) Backdrafting test, and 4) Cold Vent Establishment Pressure (CVEP) test. Results from monitoring were used to determine the reliability of the results from the stress tests. Prior to conducting combustion safety tests, a screening questionnaire, identifying house characteristics, was conducted on 188 households (74 in Washington, DC and 114 in Omaha, NE). After screening 188 houses, 90 houses (53 located in Omaha, NE [23]) were visited by local distribution companies, who provided more information regarding house tightness and venting characteristics. Of the 90 houses visited by local distribution companies, 42 houses were selected for follow-up visits by trained technicians and 16 were visited twice (58 test results total). Houses were visited during the spring. The report does not state how many of the 42 houses were located in Washington, DC and how many were in Omaha, NE. The trained technicians conducted stress tests, installed equipment for monitoring, and provided site characterization. Table 21 provides a summary of tasks completed by trained technicians. A summary of parameters recorded during monitoring is given in Table 22. A total of 42 different water heaters and 34 different furnaces were tested. Sixteen of the water heaters and furnaces were tested twice.

Table 21: Koontz et al. [35] summary of tasks completed by trained technicians for houses in Washington, DC and Omaha [35]

Component	Summary of Associated Procedure
Appliance Qualification Test	Measure background CO and CO_2 levels in the house, measure furnace/boiler and water heater combustion products in flue.
Site Characterization	Sketch house exterior and each floor, take inventory of gas appliances and exhaust devices, characterize venting system for gas furnace and water heater.
Installation of Measurement Equipment	Install laptop computer, data acquisition box, and sensors for pressures, temperatures and combustion products (CO and CO_2), program for 1 second averages during stress tests.
Measurements of House Tightness	Note local weather conditions, place house in winter (closed) configuration, use blower door to achieve prescribed depressurization levels, using Energy Conservatory data logger and Blower Door program.
Measurements/Tests of House Depressurization and Backdrafting Potential	Conduct stress tests: (1) house depressurization with preset criteria; (2) downdrafting under natural conditions and worst-case depressurization conditions; (3) backdrafting under natural conditions and worst-case depressurization conditions; and (4) CVEP.
Monitoring	Program data acquisition box for 20 to 30 second averages and instruct occupants to maintain normal practices during the monitoring period (one week). Return after one week to end data collection and remove monitoring equipment. See Table 16 for monitoring parameters.

Table 22: Koontz et al. [35] summary of monitoring parameters for houses in Washington, DC and Omaha

Parameter	Rationale and Measurement Method
Outdoor Temperature	Understand conditions under which any backdrafting or spillage occurred. Measured with a thermocouple placed in a shaded area outdoors near the house.
Indoor Temperature	Understand conditions under which backdrafting or spillage occurred, if any. Measured with thermocouples in the appliance room and living area.
Appliance Status	Confirm that suspected backdrafting events were coincident with appliance operation. Measured with thermocouple in the combustion chamber, taking care not to position too close to pilot light (if any).
Indoor-Outdoor Pressure Differential	Extent of house depressurization, to aid in interpreting potential causes of any recorded backdrafting or spillage events. Outdoor pressure taps were placed on each side of the house, near the center and base of an exterior wall, and connected to a common manifold.
Vent Pressures	A positive vent pressure, measured with reference to the appliance room, indicated times when downdrafting or backdrafting occurred. If the positive pressure was coincident with appliance operation then event is identified as backdrafting with spillage. Pressures were measured in the common vent and each appliance's vent connector, as accessible, or measurement redundancy.
Spillage Temperatures	Thermocouples were placed near appliance draft hoods at locations expected to see higher temperatures during exhaust spillage. Proper positioning to denote spillage was verified during stress tests.
Combustion Products	Investigate the indoor air quality consequences of appliance spillage. Carbon monoxide was measured with two passive electrochemical detectors, one placed in the appliance room and the other placed in the living area. If CO elevations were related to spillage, then the detector in the appliance room should rise first, and to a higher level. CO_2 was measured with a passive infrared detector placed in the appliance room. Carbon dioxide can be more sensitive to spillage events, because some appliances produce little CO when spilling. Carbon dioxide levels also are affected by the presence of occupants, whereas CO levels are not.

On Average, the tightness of the homes was 8.2 ACH50 (16.8 ACH50 maximum and 2.5 ACH50 minimum) and depressurization correlated well with the house's leakage measurement in ACH50. Houses with few to no storm windows had higher leakage than houses with storm windows (about 50% higher ACH50).

Table 23 shows that furnaces generally emitted less CO (air-free) in the combustion chamber than water heaters. The stress tests, summarized in Table 24, suggest that many of the homes tested could have problematic combustion appliances. Houses visited twice did not show repeatable stress test results (see Table 25). All four stress tests were not conducted on all water heaters and furnaces. The downdrafting test and the backdrafting test, under natural conditions, were the only two stress tests conducted on all combustion appliances.

Table 23: Technician air-free carbon monoxide measurements in Furnace and Water heater combustion chambers from 40 houses in Washington, DC and Omaha (1999) [35]

Measurement Location	Air-free CO in Washington Homes (ppm)				Air-free CO in Omaha Homes (ppm)			
	Mean	Median	Max	≥100ppm	Mean	Median	Max	≥100ppm
Furnace								
- 1st Chamber	6.8	1.0	68	0.0%	5.7	1.0	100	2.0%
- 2nd Chamber	4.7	0.0	40	0.0%	3.0	1.0	42	0.0%
- 3rd Chamber	3.3	0.0	30	0.0%	3.2	1.0	42	0.0%
- 4th Chamber	4.0	1.0	30	0.0%	4.9	1.0	42	0.0%
Water Heater								
- 1st Chamber	24.0	0.0	290	5.7%	22.5	0.0	998	2.0%
- 2nd Chamber	6.0	3.0	50	0.0%	1.2	1.0	4	0.0%

Table 24: Summary of stress test results for houses in Washington, DC and Omaha (1999) [35]

Test Method	Percentage (Fraction) of Cases Not Meeting Test Criteria		
	House	Water Heaters	Furnaces
House Depressurization with Preset Criteria	29% (16/56)		
Downdrafting			
- Natural conditions		38% (22/58)	30% (15/50)
- Worst case conditions		48% (27/56)	42% (21/50)
Backdrafting			
- Natural conditions		22% (12/58)	8% (4/49)
- Worst case conditions		29% (16/56)	12% (6/49)
CVEP		38% (22/58)	26% (12/48)

Table 25: Repeatability of stress tests for Washington, DC and Omaha houses visited twice (1999) [35]

Test Method	Percentage (Fraction) of Cases with the Same Test Result		
	House	Water Heaters	Furnaces
House Depressurization with Preset Criteria	73% (11/15)		
Downdrafting			
- Natural conditions		75% (12/16)	81% (13/16)
- Worst case conditions		81% (13/16)	75% (12/16)
Backdrafting			
- Natural conditions		69% (11/16)	81% (13/16)
- Worst case conditions		69% (11/16)	81% (13/16)
CVEP		56% (9/16)	60% (9/15)

The authors also compared results between stress tests and found the following trends:

- Water heaters that failed (did not meet the criteria for) the downdrafting test under natural conditions almost always failed the downdrafting test under worst-case conditions.
- Water heaters that passed (met the criteria for) the downdrafting test under natural conditions almost always passed the backdrafting test under worst-case conditions and the CVEP test.
- Water heaters that failed the backdrafting test under natural conditions failed the backdrafting tests under worst-case conditions and almost always failed the CVEP test.
- Furnaces that failed the downdrafting test under natural conditions almost always failed the downdrafting test under worst-case conditions; similar results were found for the backdrafting test under natural and worst-case conditions.
- Furnaces that passed the downdrafting test under natural conditions passed the backdrafting test under natural conditions and passed the worst-case backdrafting test.
- Furnaces that passed the worst-case downdrafting test also passed the natural and worst-case backdrafting tests
- Furnaces that failed the natural or worst-case backdrafting test, also failed the CVEP test

A summary of these trends including results can be found in Table 26 for water heaters and Table 27 for furnaces.

The report also compares house depressurization with outdoor temperature during monitoring. The results showed that houses were slightly more depressurized, on average, during the monitoring than during the trained technician visits. Additionally, houses that were visited twice showed higher depressurization when the temperature was colder outside. The authors note that the average outdoor temperature during the continuous tests is lower than that for the stress tests, likely because the stress tests were typically performed during daylight hours.

Although the stress tests indicated spillage potential in a significant percentage of the houses tested, there was little to no sustained spillage or backdrafting recorded during monitoring of the houses. The worst-case downdrafting test predicted 40 to 50% of appliances tested had downdrafting potential. The CVEP test predicted 40% of water heaters and 25% of furnaces had backdrafting or spillage potential. The natural and worst-case backdrafting test predicted 25% of water heaters and 10% of furnaces were prone to backdrafting. The repeatability (passing or failing the test consistently) of most stress tests was around 75%. The CVEP test had the poorest repeatability of 60%.

The monitoring results showed that positive pressures measured in vents were most often downdrafting events when the appliance was off or caused by an induced draft fan during appliance start-up. Additionally, CO and CO_2 concentrations showed no spillage during appliance operation, but showed some brief spillage during appliance start-up. Table 28 provides a summary of CO and CO_2 measurements. Durations for the maximum CO and CO_2 measurements were not provided.

In conclusions, the authors recommend extreme caution when interpreting results from stress tests, as the stress tests tend to over-classify houses as spillage-prone. Additionally, the authors state that spillage temperatures are not a reliable indicator of spillage events because thermal radiation from gases flowing near the draft diverter can be mistaken for small amounts of spillage, or vice versa. Monitoring should also be conducted for longer periods of time.

Table 26: Summary of coincident stress test results for water heaters noted by authors for houses in Washington, DC and Omaha (1999) [35]

Test Method			Downdraft, Worst-Case (Cases)	Backdraft, Natural (Cases)	Backdraft, Worst-case (Cases)	CVEP (Cases)
Downdraft, Natural	Pass	36		Pass (32/34)	Pass (28/29)	Pass (28/29)
	Fail	22	Fail (19/20)			
Downdraft, Worst-Case	Pass	29		Pass (27/28)	Pass (27/28)	Pass (27/28)
	Fail	27				
Backdraft, Natural	Pass	46				
	Fail	12			Fail (10/10)	Fail (10/11)

Table 27: Summary of coincident stress test results for furnaces noted by authors for houses in Washington, DC and Omaha (1999) [35]

Test Method			Downdraft, Worst-Case (Cases)	Backdraft, Natural (Cases)	Backdraft, Worst-case (Cases)	CVEP (Cases)
Downdraft, Natural	Pass	35		Pass (34/34)	Pass (33/34)	
	Fail	15	Fail (14/15)			
Downdraft, Worst-Case	Pass	29		Pass (28/28)	Pass (28/28)	
	Fail	21				
Backdraft, Natural	Pass	45			Pass (41/43)	
	Fail	4			Fail (4/4)	Fail (3/3)
Backdraft, Worst-Case	Pass	43				
	Fail	6				Fail (5/5)

Table 28: Summary of CO and CO_2 concentrations from one-week of monitoring houses in Washington, DC and Omaha (1999) [35]

Mean CO in CAZ (ppm)	Mean CO in Living Room (ppm)	Max CO in CAZ (ppm)	Max CO in Living Rom (ppm)	Mean CO_2 in CAZ (ppm)	Mean CO_2 in Living Room (ppm)
1.5	1.1	8.3	8.7	639	1191

Note: The mean CO and CO_2 were obtained by averaging the data from a single house and then averaging that mean value with all other house mean values. The maximum CO and CO_2 values were obtained by averaging the maximum reading from each home.

Initial Surveys on Depressurization-Induced Backdrafting and Spillage: Volume II - Twin Cities, MN (1999)

In this report, Grimsrud et al. [23] investigated houses in the Twin Cities, MN, continuing the research conducted by Koontz et al. [35]. This study uses the same protocols and procedures as those used by Koontz et al. [35] in Washington, DC and Omaha, NE. Like the previous report, the purpose of this research was to assess the correspondence between the possibility and occurrence of backdrafting using stress tests and monitoring, as outlined in the ASTM E1998 [3]. A summary of tests conducted and measured parameters for the one-week monitoring can be found in Tables 21 and 22, respectively.

A total of 52 houses in metropolitan Minneapolis/St. Paul, MN were administered screening questionnaires by telephone. From the questionnaire, results showed that most appliances were located in the basements of houses and did not contain vent dampers. Local distribution companies, who provided more information regarding house tightness and venting characteristics, visited 21 of the 52 houses screened. The local distribution companies found that most (~95%) of the houses in Minneapolis/St. Paul and Omaha, NE had proper vent size or pitch. However, only 38% of the houses in Minneapolis/St. Paul had properly sized combustion air supplies. It should be noted that results from the Minneapolis/St. Paul houses are compared with the Omaha, NE houses and the report states that 53 houses in Omaha, NE were visited by local distribution companies.

Of the 21 houses visited by local distribution companies in Minneapolis/St. Paul, 14 were selected for follow-up visits by University of Minnesota field staff. The University of Minnesota field staff also visited an additional 14 houses (28 houses total) not visited by local distribution companies and conducted the protocols outlined in Table 21. Some of the 28 houses were visited twice, but an exact number was not provided. Houses were visited during the late winter and early spring. On average, the tightness of homes was 6.7 ACH50 (3.1 ACH50 minimum and 12.2 ACH50 maximum).

A summary of the stress test results is given in Table 29 and includes houses that were visited twice. The author notes that the CVEP test was affected by wind and that repeat tests in houses showed 20% variation (a high estimate) in results when performed on windy days. The stress test results suggest that many of the homes tested could have problematic combustion appliances. Additionally, appliances that failed the worst-case downdrafting test usually failed the worst-case backdrafting test and the CVEP test, as shown in Tables 30 and 31. Unlike the homes in Omaha and Washington, D.C., the Minnesota homes showed furnaces emitting slightly more CO (air-free) than water heaters (see Table 32).

Table 29: Summary of stress test results in Minneapolis-St. Paul houses (1999) [23]

Test Method	**Percentage (Fraction) of Cases Not Meeting Test Criteria**		
	House	**Water Heaters**	**Furnaces**
House Depressurization Test with 5 Pa Criteria	28% (8/29)		
Downdrafting Test - Worst case conditions		38% (11/29)	41% (13/32)
Backdrafting Test - Worst case conditions		27% (8/30)	16% (5/32)
CVEP Test		31% (9/29)	17% (5/29)

Table 30: Summary of noteworthy trends when comparing stress test results for water heaters for houses in Minneapolis-St. Paul (1999) [23]

Test Method		Backdraft, Worst-case (Cases)	CVEP (Cases)
Downdraft, Worst-Case	Pass		
	Fail	Fail (16/17)	Fail (16/17)
Backdraft, Worst-Case	Pass		Pass (8/8)
	Fail		Fail (19/20)

Table 31: Relationship between stress test results for furnaces for houses in Minneapolis-St. Paul (1999) [23]

Test Method		Backdraft, Worst-case (Cases)	CVEP (Cases)
Downdraft, Worst-Case	Pass		
	Fail	Fail (19/19)	Fail (15/16)
Backdraft, Worst-Case	Pass		Pass (3/4)
	Fail		Fail (22/23)

Results from monitoring, conducted for one week, showed that houses were depressurized about the same amount during monitoring and during the field staff visits. Additionally, over half the houses tested showed positive vent pressure at some point during the week of testing, but only a few indicated actual spillage events. Most spillage events occurred for several minutes during appliance start-up or occurred when two appliances, connected to a common vent, were operating at the same time. Table 33 provides a summary of CO and CO_2 measurements. Durations for the maximum CO and CO_2 measurements were not provided.

The authors conclude that stress tests suggested many houses were vulnerable to backdrafting and spillage, but few cases of backdrafting and spillage were actually observed during continuous tests. The authors recommend that stress tests be interpreted with caution, especially results from the worst-case backdrafting test. Houses that showed positive vent pressures were often downdrafting events (with the combustion appliances off), not backdrafting or spillage events. The authors suggest a house fail multiple (though unspecified number of) stress tests before it is considered spillage-prone. They also recommend that monitoring should take place over longer periods of time (minimum one week) before making any definitive conclusions about the accuracy of stress tests results.

Table 32: Technician air-free carbon monoxide measurements in Furnace and Water heater combustion chambers from 28 houses in Minnesota (1999) [23]

Measurement Location	Air-free CO in Minneapolis–St. Paul Houses (ppm)			
	Mean	Median	Max	≥100ppm
Furance				
- 1st Chamber	11	10	45	0.0%
- 2nd Chamber	11	10	45	0.0%
- 3rd Chamber	12	10	45	0.0%
- 4th Chamber	12	10	45	0.0%
Water Heater	9	5	25	0.0%

Table 33: Summary of CO and CO_2 concentrations from one-week of monitoring from 28 houses in Minnesota (1999) [23]

Mean CO in CAZ (ppm)	Mean CO in Living Room (ppm)	Max CO in CAZ (ppm)	Max CO in Living Rom (ppm)	Mean CO_2 in CAZ (ppm)	Mean CO_2 in Living Room (ppm)
0.6	1.4	4.5	7.7	682	1355

Note: The mean CO and CO_2 were obtained by averaging the data from a single house and then averaging that mean value with all other house mean values. The maximum CO and CO_2 values were obtained by averaging the maximum reading from each home.

Surveys on Depressurization-Induced Backdrafting and Spillage (1999)

In this article, Grimsrud et al. [24] summarized data and results collected in the two GRI reports written in 1999 [23, 35] that assess the relationship between stress tests and one week of monitoring. Stress test and continuous tests, listed in ASTM E1998 [3], were conducted on 181 houses in Washington DC, Omaha, NE, and Minneapolis-St. Paul, MN. The results show that sustained backdrafting events were rare during the monitoring. From this study, stress tests under induced conditions significantly overstated the likelihood of backdrafting and spillage.

Blower door tests were conducted to measure house air-tightness. This study investigated established houses, not new construction. Minneapolis houses were slightly tighter than houses located in Washington DC and Omaha. Failure rates of stress tests were 30% for downdrafting tests and 40% for backdrafting tests. The majority of failing appliances were water heaters.

Based on results from houses that were visited twice, downdrafting tests had the best repeatability. The strongest correspondence across different types of stress test was between the results of the appliance backdrafting test and the CVEP test for both furnaces and water heaters.

Monitoring was started on the same day that stress tests were conducted to match weather conditions. Outdoor temperatures were between 46 and 40°F. Monitoring rarely showed positive pressures in the vent during appliance operation. Spillage zone temperatures were difficult to interpret because the authors could not distinguish between temperatures showing thermal radiation from heated gases and temperatures showing small amounts of spillage.

Spillage prone houses were monitored additionally with CO and CO_2 monitors. The results show that concentrations of CO and CO_2 increased at startup but elevated concentrations were not sustained. Increases in CO and CO_2 were often attributed to environmental conditions (e.g., unvented appliance, automobiles) instead of the combustion appliance. Water heaters with vent dampers spilled pollutants from the pilot burner (by design) when the main burner was off.

The authors conclude that sustained backdrafting events were rare according to their real-time monitoring results. Additionally, stress tests poorly predicted actual backdrafting events and overstated the occurrence of backdrafting and spillage. Longer monitoring may capture more spillage events. Additionally, the authors suggested that follow-up research should include backdrafting and spillage stress tests and monitoring during hot weather conditions, as this research conducted experiments during winter weather conditions only.

Follow-Up Survey on Depressurization-Induced Backdrafting and Spillage in Omaha Residences (2001)

In this report, Koontz et al. [34] conducted a detailed examination of backdrafting and spillage potential by re-visiting a subset of Omaha, NE houses tested in 1999 [35]. Houses were monitored over a period of months, covering multiple seasons to gain a better understanding of characteristics leading to backdrafting or spillage. Houses were selected to provide a range of characteristics and degree of apparent proneness to backdrafting. Results are compared to results collected in 1999 [35].

Stress tests outlined in ASTM E1998 [3] were conducted on nine houses and five of the houses were visited twice. All nine houses tested had venting chimneys located in the middle of the house. A summary of stress tests results is provided in Table 34. CO measurements taken during the CVEP test are provided in Table 35.

The monitoring, lasting two to six months, showed little indication of spillage even on the most "prone to spillage" houses under natural conditions. Nine houses of the 42 originally studied were deemed spillage prone and were monitored for longer periods. In these houses, they performed the following three stress tests: 1) depressurization test, 2) worst-case downdrafting test, and 3) worst-case backdrafting test on houses.

This study is one of the first to primarily focus on how weather conditions affect stress test results. Effects of wind speed on the stress test failure are listed in the Table 36. According to the results, houses were more likely to fail stress tests during low wind speeds (< 1 mph) than high wind speeds (> 8 mph). Table 37 shows the effects of outdoor temperature on stress test failure.

Table 34: Summary of stress test results from nine Omaha houses (2001) [34]

Test Method	**Percentage (Fraction) of Cases Not Meeting Test Criteria**		
	House	**Water Heaters**	**Furnaces**
House Depressurization Test with 5 Pa Criteria	28% (4/14)		
Downdrafting Test - Natural conditions - Worst case conditions		 57% (8/14) 64% (9/14)	 57% (8/14) 64% (9/14)
Backdrafting Test - Natural conditions - Worst case conditions		 36% (5/14) 50% (7/14)	 21% (3/14) 21% (3/14)
CVEP Test		57% (8/14)	23% (3/13)

Table 35: Summary of air-free CO concentrations measured during CVEP test from houses in Omaha (2001) [34]

House ID	CO (Air-free)	
	Furnace	Water Heater
N508	625	
N529	580[1]	
N545	360	
N575		120
N584		110
N588	600	
N602		140

[1]Measured during worst-case backdrafting test

The relationship between stress test failure and outdoor temperature is somewhat unclear. Houses appear less likely to fail a downdrafting tests in warm weather. However, water heaters were the most spillage prone in warm weather conditions (outdoor temperature > 60°F).

The monitoring showed that positive pressures in the vents usually occurred when the appliance was not operating (downdrafting events). Temperature sensors provided misleading results for spillage events as the temperature threshold was chosen arbitrarily and could be confused with thermal radiation from the appliance. Data from two of the nine houses (N520 and N554) showed highly elevated temperatures, indicating spillage, but both houses were equipped with vent dampers, which "spill" by design when the appliance is not operating. Although spillage did occur in these two houses, the frequency was rare and short in duration (less than 1 minute) during appliance start-up. Table 38 provides a summary of CO and CO_2 measurements taken in the living space for each house.

The authors conclude that stress tests overstate the potential significance of spillage. During the summer months, water heaters were more prone to spillage, but the authors regard this as a minor concern.

Table 36: Outcomes of stress tests (percent "failing") by wind velocity for houses in Omaha (2001) [34]

Wind Speed (mph)	CGSB Test	Initial Downdrafting Test	Worst-case Downdrafting Test	Water Heater Backdrafting Test	Furnace Backdrafting Test
<1	33% (3)	0% (1)	100% (1)	67% (3)	0% (1)
1-3	37% (24)	30% (20)	45% (20)	33% (24)	20% (20)
4-7	50% (6)	0% (6)	17% (6)	14% (7)	0% (5)
>8	0% (2)	0% (2)	0% (2)	0% (2)	0% (2)

Note: The number of cases on which each percentage is based is shown in parentheses

Table 37: Outcomes of stress tests (percent "failing") by outdoor temperature for houses in Omaha (2001) [34]

Outdoor Temperature (°F)	CGSB Test	Initial Downdrafting Test	Worst-case Downdrafting Test	Water Heater Backdrafting Test	Furnace Backdrafting Test
20-30	50% (6)	17% (6)	33% (6)	33% (6)	0% (6)
30-40	57% (14)	22% (14)	43% (14)	36% (14)	30% (14)
40-60	28% (7)	14% (7)	28% (7)	0% (7)	0% (6)
>60	0% (8)	0% (2)	0% (1)	44% (9)	0% (2)

Note: The number of cases on which each percentage is based is shown in parentheses

Table 38: Summary of CO and CO_2 concentrations measured in the living space from houses in Omaha (2001) [34]

House ID	Mean* CO (ppm)	Max** CO (ppm)	Mean* CO_2 (ppm)	Max** CO_2 (ppm)
N501	2.5	6.2	549	492
N505	4.3	7.1	695	1112
N508	0.5	1.9	627	668
N520	2.7	6.0	1206	3075
N529	1.9	2.5	492	750
N545	0.8	1.8	759	855
N554	1.5	2.4	583	1169
N556	4.6	5.8	547	1144
N588	0.8	1.6	633	695

* Mean of weekly averages
** Max weekly average

Depressurization-Induced Backdrafting and Spillage: Implications of Results from North American Field Studies (2002)

In this article, Koontz et al. [33] compared field studies, collected between 1980 and 2000, assessing depressurization, backdrafting, and spillage in residential houses located in Canada and the United States. The article specifically compares results from the four depressurization-induced backdrafting and spillage test (stress tests) and the two monitoring outlined in ASTM E1998 [3]. Backdrafting and spillage events indicated by the continuous tests, were considered actual events. After comparing results from previous research, the authors show that stress-induced tests are not reliable indicators of spillage potential and are too conservative when predicting spillage. Continuous test results suggested that many of the stress-induced tests predicted misleading failures (failing houses when backdrafting is not actually problematic). The authors also state that spillage is more likely to occur from water heaters than from furnaces. Additionally, houses in colder climates tend to have tighter envelopes, leading to higher natural and induced depressurization levels that increase the potential for spillage. For monitoring, the authors suggest a minimum monitoring period of one week for predicting spillage potential of a house. They also suggest monitoring the following parameters for continuous tests, as temperature alone does not provide a reliable indication of spillage: pressure in the common vent, CO and CO_2 concentrations in the appliance room, and on/off status of the appliance being monitored.

Depressurization-Induced Backdrafting and Spillage: Assessment of Test Methods (2002)

Nagda et al. [44] assessed all the backdrafting and spillage procedures outlined in ASTM E1998-11 using the same data collected by Koontz et al. in 1999 [35]. The data were taken from 42 houses in Washington DC and Omaha, NE. Of the 42 houses, 16 were visited and monitored on two separate occasions, once in the summer or fall and once in the winter. Houses were chosen based on their propensity for backdrafting. On average, selected houses had a base depressurization of 1.9 Pa. Their results showed that none of the houses exhibited any significant backdrafting or spillage, based on monitoring test procedures. All occurrences of positive pressure in the vent or backdrafting were caused by an induced draft fan or were transitional events lasting less than one minute. Stress tests indicated 10 to 40% of study houses might be spillage-prone, while monitoring under real-life conditions showed spillage was rare.

The average baseline depressurization level was -1.9 Pa, with a range from -5.2 to +0.4 Pa. Initial depressurization due to exhaust appliances averaged around -3.4 Pa and ranged from -8.0 to -0.6 Pa. Conducting worst-case depressurization gave a mean value of -4.0 Pa with a range of -14.3 to -0.7 Pa.

The worst-case downdrafting test had the highest failure rate (without appliance operation). When the appliance was operated, the CVEP test had the highest failure rate of all the tests. The water heater did not meet the criterion for appliance backdrafting test about twice as often as for furnaces, suggesting water heaters have greater backdrafting potential than furnaces. Furnaces with induced-draft fans had CVEP values about 50% higher than those without induced-draft fans. Water heaters had a lower CVEP value than furnaces (a lower CVEP value means that the appliance is expected to have a weaker draft or is less able to overcome a downdraft condition).

For monitoring, positive pressure in the vent occurred with induced draft furnaces only during start-up. Water heaters had positive pressure about 1.5 minutes per day, usually during start-up. Most positive pressures measured in vent connectors were downdrafting events (both appliances off).

Houses that were predicted to be more spillage prone were installed with CO and CO_2 monitors. The maximum concentration of CO was 8.3 ppm in the mechanical room and 8.7 ppm in the living room. Most of the houses had CO concentrations below 9 ppm and CO_2 levels below 1000 ppm. Averaging time was 15 seconds, so their results are very conservative (most standards suggest a one-hour average).

The author's concluded that monitoring of pressures in the common vent showed no instances of sustained backdrafting. Positive pressure measurements inside the vent were usually due to start-up of the induced-draft fan furnace. Water heaters have greater backdrafting potential than furnaces. Average indoor-air concentrations of CO were low. Stress tests did not always agree with continuous tests. The authors are uncertain of the credibility of the stress tests. They believe continuous tests are more indicative of spillage events and that stress tests are misleading. Their results indicate that the collection of indicators provides a better indication of backdrafting than does any one indicator. Note: weather conditions (wind speed or air temperature) and house leakage data were not provided.

Ventilation and Depressurization Information for Houses Undergoing Remodeling (2002)

In this report, Bohac et al. [7] investigated the ventilation of houses tightened by the Sound Insulation Program (SIP) for the Minnesota Department of Commerce. Houses near the Minneapolis-St. Paul International Airport were acoustically treated to reduce the interior sound level by 5 dBA. Depending on the house, treatment could include new windows, storm doors, roof vent baffles, wall insulation, attic insulation, chimney vent caps, air sealing, air conditioning, and replacement furnace. Due to the large number of houses tested, venting during a variety of seasons was captured. If venting of an appliance failed during the summer months, then the house was re-tested at the beginning of the heating season.

Houses in Minneapolis-St. Paul were tested both before and after the SIP treatment, but combustion spillage data for vented appliances is only reported for tests conducted *before* the SIP treatment. Flue Carbon Monoxide (CO) test results are reported for both before and after the SIP treatment for ovens. A summary of the methods used for assessing combustion safety can be found in Table 39. Table 40 provides the depressurization limit guideline for the worst-case depressurization test. For the flue carbon monoxide test, 3% of natural draft water heaters and 8% of the furnaces failed the CO standard of 100 ppm. The furnace failure rate almost doubled when the test was performed under downdraft conditions (see Table 41). CO measurements in the flue were "as measured" and not adjusted for excess combustion air (air-free). A distribution of CO measurements for each appliance can be found in Table 42.

Table 39: Bohac et al. (2002) [7] summary of methods used for assessing combustion safety of houses in Minneapolis-St. Paul

Test Name	Measurements Recorded	Test Requirements	Appliances Tested
Flue Carbon Monoxide	• Carbon monoxide measured after 5 minutes of burner operation	• CO < 150 ppm for ovens/ranges • CO < 100 ppm for vented appliances	• Ovens • Water Heaters • Boilers • Furnaces
BPI Worst-Case (WC) Depressurization	• Pressure differential between CAZ and outside	See Table 21	• Water Heaters • Boilers • Furnaces
Combustion Vent Spillage	• Draft (using smoke) • Temperature at three locations around draft hood	• Conduct test at WC depressurization and Natural Conditions • No spillage after 1 min for furnaces • No spillage after 3 min for water heaters and boilers • Spillage occurs when average temperature difference between draft hood and CAZ > 44°F or temperature difference between one draft hood sensor and CAZ > 55°F	• Water Heaters • Boilers • Furnaces
Combustion Vent System Design	• Vent system construction (size, vent type, vent connectors, elbows, etc.)	See vent capacity tables in National Fuel Gas Code [39]	• Water Heaters • Boilers • Furnaces

Table 40: Bohac et al. (2002) [7] depressurization limit guideline for houses in in Minneapolis-St. Paul

Appliance Type	Depressurization Limit (Pa)
Individual (orphan) water heater (WH)	-2
Natural draft WH and furnace or boiler	-3
Induced draft furnace/boiler & natural draft WH	-5
Individual natural draft furnace or boiler	-5
Individual induced draft furnace of boiler	-15
Common vent with chimney-top draft inducer	-15
Power vented and sealed combustion	>25

Table 41: Summary of results for flue carbon monoxide test for houses in Minneapolis-St. Paul (2002) [7]

Appliance	Total Tested	Percent Failed Test
Oven	2,891	25% (before treatment) 7% (after treatment)
Water Heater (when venting)	1,356	3%
Water Heater (during DD*)	1,356	5%
Furnace (when venting)	548	8%
Furnace (during DD*)	548	14%

* DD indicates that the test was conducted while down drafting was induced

Table 42: Distribution of natural gas appliance carbon monoxide measurements for houses in Minneapolis-St. Paul (2002) [7]

Range (ppm)	Oven			Water Heater		Natural Draft Furance	
	2 min	5 min	Steady	Normal	DD	Normal	DD
<= 25	4%	15%	27%	90%	88%	85%	78%
25-50	4%	21%	27%	5%	5%	5%	5%
50-100	10%	26%	23%	1%	2%	2%	2%
100-150	9%	13%	10%	0%	1%	2%	2%
150-250	17%	12%	7%	1%	1%	1%	2%
250-500	28%	9%	4%	1%	1%	1%	2%
> 500	28%	4%	2%	2%	2%	4%	7%

* Measurements conducted when the appliances are venting properly
** Measurements conducted while a down-draft was induced

The worst-case (WC) depressurization test was conducted on 1,427 houses. Houses were selected based spillage potential. The WC depressurization test was used as a design guideline to predict the likelihood of a depressurization problem after a house has been tightened and exhaust ventilation added. To compensate for fluctuations in pressure reading during windy conditions, a computer was used to estimate WC depressurization using exhaust fan flow rate and measured depressurization. The authors note that orphaned water heaters proved to be the most susceptible to depressurization induced combustion spillage problems, as 36% failed the WC depressurization test. Other appliances proved to be less problematic, as shown in Table 43. It should be noted that these results do not necessarily imply that orphaned water heaters are more susceptible to spillage; instead, orphaned water heaters are more likely to fail worst-case depressurization because they have the lowest threshold.

The combustion spillage test was conducted on 1,303 natural draft water heaters and 554 natural draft furnaces under worst-case depressurization conditions and natural conditions. As shown in Table 44, 11% of natural draft water heaters and 4% of furnaces fail the spillage test under worst-case and natural conditions. These spillage failure results are consistent with those reported by Nagda et al. [44], showing almost twice as many water heaters fail than furnaces.

Further analysis was conducted to examine how the venting system design of water heaters affected combustion spillage. The results show that 25% of water heaters with transite (asbestos insulated) liners failed, while 12% to 14% of water heaters with tile and exterior tile failed (see Table 45).

The impact of vent connector size on combustion spillage was also investigated. The results showed that connectors undersized up to 40% had an average failure rate under natural conditions of only 10%. Connectors undersized by more than 40% had a failure rate of 31%. The author suggests that venting systems designed to meet the requirements in the National Fuel Gas Code (NFGC) tables have a high likelihood of venting properly, but systems that are undersized are not guaranteed to fail.

The following conclusions are made in this report:

- Combustion venting systems that meet the design guidance in the National Fuel Gas Code tables [39] have a high probability of venting properly.
- Depressurization for common vent water heaters should be no more than 5 Pa. A depressurization limit of 3 Pa can be set for a 5 to 20% failure rate for all outdoor conditions.
- Monthly tracking of spillage failure suggests that spillage failures are more frequent during warmer outdoor conditions. Results show spillage failure drops significantly when the outdoor temperature is less than 40ºF.
- Appliances that fail under natural conditions are likely to spill under most conditions.
- A standard "clean and tune" maintenance of a furnace can reduce elevated CO under downdraft conditions.
- The downdrafting test may be an indication of water heaters starting to go "out of tune," but this theory has not been verified.

Table 43: Summary of results for worst-case depressurization test for houses in Minneapolis-St. Paul (2002) [7]

Appliance Type	Depressurization Limit	Percent Failed Test*
Individual (Orphan) water heater (WH)	2	36%
Natural draft WH and furnace/boiler	3	12%
Induced draft furnace/boiler & natural draft WH	5	5%
Individual natural draft furnace/boiler	5	5%
Individual induced draft furnace/boiler	15	0%
Common vent with draft inducer	15	0%
Power vented and sealed combustion	>25	0%

* Percentage of houses with measured depressurization greater than the listed limit

Table 44: Combustion spillage test results for houses in Minneapolis-St. Paul (2002) [7]

	Natural Draft Water Heater	Natural Draft Furnace
Percent Passed Both WC and Nat.*	81%	90%
Percent Failed WC and Passed Nat.	9%	6%
Percent Failed Both WC and Nat.	11%	4%

* "Nat." implies the test was conducted under natural conditions.

Table 45: Water heater spillage test results by chimney type for houses in Minneapolis-St. Paul (2002) [7]

Chimney Type	Pass Both	Fail WC Pass Nat.*	Fail Both
Interior Tile	75%	11%	14%
Exterior Tile	81%	7%	12%
B-vent	83%	10%	6%
Transite	71%	4%	25%
Interior Tile with Metal Liner	86%	7%	7%
Exterior Tile with Metal Liner	78%	9%	13%

* "Nat." implies the test was conducted under natural conditions.

Residential Combustion Spillage Monitoring (2004)

Fugler [19] presented a research highlight about combustion spillage research that was conducted for the Canada Mortgage and Housing Corporation, which was first published in 1987, but never released. The purpose of this study was to perform more detailed monitoring on houses that experienced combustion spillage. Monitoring activities were performed on 16 houses and carried out over a period of 14 to 35 days. A data acquisition system recorded appliance status (on/off), occurrence of spillage, if windows and doors were open, if exhaust fans were operating, and if the fireplace was in use. Thermistors were used to determine combustion appliance status and indicate spillage.

Houses that showed significant spillage (10 seconds of spillage for gas-heated house and 5 seconds for an oil-heated house) were further investigated to determine the effects of spillage on indoor air quality. Houses that were forced to spill gave high readings of CO_2 and sulfur dioxide (SO_2); however, houses with naturally occurring spillage had levels that would not be considered hazardous.

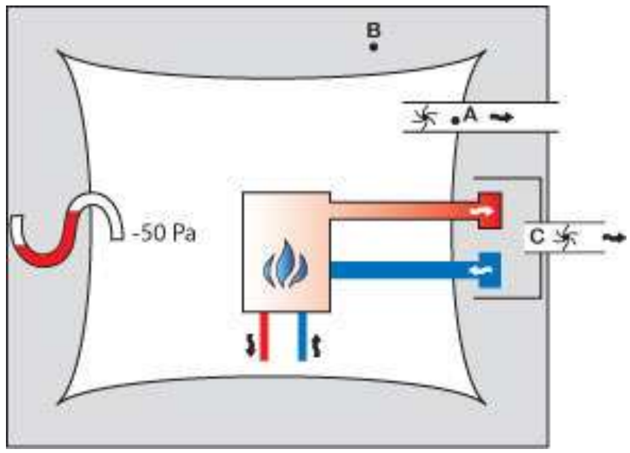
Overall, the results indicate that combinations of environmental and house operation characteristics most conducive to combustion spillage are rare. Appliance and venting system configuration have a stronger correlation with spillage events than effects of outside temperature and wind. Poor chimney performance is likely the largest contributing factor to combustion spillage. The authors suggest emphasis be placed on improving chimney performance to prevent combustion spillage.

Development and Evaluation of a New Depressurization Spillage Test for Residential Gas-Fired Combustion Appliances (2005)

This report [15] describes the development of a new depressurization test for combustion appliance manufacturers and certification agencies to differentiate products in terms of spillage resistance. The test is also designed to help manufacturers develop and market more spillage-resistant combustion appliances. To develop the new depressurization test, the performance of seven residential combustion appliances was evaluated in a Canadian commercial testing laboratory. The following appliances were tested: two power-vented, storage-tank water heaters; one code-compliant, "mid-efficiency", natural draft furnace; two high efficiency condensing furnaces; and two direct-vent gas fireplaces.

The concept of the depressurization spillage test is shown in Figure 6. The box with a flame represents a combustion appliance installed in the depressurized test room. The horizontal ducts colored red and blue represent the combustion air inlet and combustion gas vent. A direct vent combustion appliance is shown in Figure 6, but not all appliances tested were direct vent appliances. The fan installed in duct "A" was used to depressurize the room and discharged outside the building. A supplemental exhaust system, located at “C”, captured and removed combustion products to avoid contaminating the area adjacent to the room, location “B”.

Figure 6: Simplified concept of depressurization spillage test taken from the report [15]



The test used CO_2, produced in the combustion process, as a tracer gas, to determine spillage. The amount of combustion spillage was determined by dividing the amount of CO_2 released into the test room from the appliance and its combustion venting system during the test cycle by the amount of CO_2 produced by combustion of the fuel that was consumed during the test. The ratio of the two provides a direct measure of the combustion spillage of the appliance and its venting system during each test in percent. For natural gas, the same CO_2 production factor was used in all calculations. They calculated both volumetric and unit energy CO_2 production factors.

Each unit was initially tested at 50 Pa depressurization. If combustion spillage of the unit exceeded 2% (CO_2 measured from spillage in test room divided by CO_2 fuel-predicted), then the test was repeated at 20 Pa depressurization. If the measured spillage exceeded 2% at 20 Pa, a final test was performed at 5 Pa depressurization.

Appliances were operated for a five minute period of burner operation with the room depressurization level controlled at the selected value. The burner fuel consumption, the concentration of CO_2 in the test room, and the exhaust fan flow rate were monitored throughout the five minute combustion period. Measurements were continued for two minutes immediately following the burner shutoff to capture transient combustion products.

The depressurization test protocol can be summarized as follows:

- Prepare the appliance by operating it for at least four hours to allow removal of manufacturing residues.
- Adjust the pressure inside the test room to the desired depressurization level.
- Position the CO_2 monitor inside the test room between 0.5 and 1m from the appliance burner.
- Operate the appliance at its maximum firing rate.
- Measure and record the CO_2 levels in the test room, the test room depressurization, and the appliance fuel consumption rate every 30 seconds for a total of seven minutes.

- After five minutes of operating the appliance, shut off fuel to the appliance to turn off the burner and continue to collect data for an additional two minutes (seven minute test total).
- If the appliance draws combustion air from inside test room, the CO_2 content and temperature in the combustion venting system at the vent termination shall be monitored during the test to establish the excess-air level in the combustion vent.
- The CO_2 content of the space adjacent to the test room should be measured immediately before and immediately after the seven-minute test to ensure contamination has not occurred. Install the combustion appliance in a well-sealed room

The results show that at 50 Pa depressurization, three of the appliances had essentially undetectable levels of combustion spillage. Three other appliances had low, but measurable combustion spillage (between 0.7 and 1.5%). One appliance had significant combustion spillage (13%). The appliance with significant spillage at 50 Pa depressurization displayed 3.5% spillage at 20 Pa depressurization. All other appliances had no measurable spillage at 20 Pa depressurization. At 5 Pa depressurization, all the appliances had no measurable spillage.

Ambient air contains about 425 ppm of CO_2, but can change from day to day. Calculations for combustion spillage take into account change of background CO_2. Combustion gases exhausted far away from the test area so they did not interfere with measurements. When vented directly into the room, CO_2 levels achieved about 1400 ppm. Only about 85% of the CO_2 was accounted for when they vented directly into the room and used their method (perhaps due to incomplete combustion).

Additionally, oscillations in measurements were on the order of 15 ppm. Therefore, differentiating between a close "pass" and close "fail" could be difficult. Repeatability of tests was about 4%. It must be stressed that only one sample of each appliance was actually tested in this project. Sample to sample production changes and differences in the installation methods or materials may produce different results.

The authors conclude that the test is a simple method of differentiating products that spill and do not spill. Mostly, this tool is developed for combustion appliance manufacturers to test their appliances under different depressurization conditions. Additionally, the 2% spillage limit threshold was chosen to allow for flexibility in choice of instrumentation. This is the same tolerance allowed in the static vent leakage tests for the combustion vent section of sealed combustion appliances that operate with positive vent pressures.

Depressurization Spillage Testing of Ten Residential Gas-Fired Combustion Appliances (2008)

This report [16] builds on similar research carried out in 2005, report titled, "Development and Evaluation of a New Depressurization Spillage Test for Residential Gas-Fired Combustion Appliances" [15], which evaluated the performance of a small sample of residential combustion appliances using a new depressurization spillage test procedure. Ten more new direct vent or power vent "spillage-resistant" gas appliances were tested at the same laboratory as the 2005 tests. The results of the new experiments were similar to those for the 2005 tests. At 50 Pa depressurization, five appliances had no measureable spillage. Three had low, but measureable spillage and two had more than 2% spillage, including one with over 10% spillage. Overall, combustion appliances that are designed to be spillage resistant do not perform as well as advertised, though they are much more resilient than natural draft appliances when interior depressurization occurs. This report further supports manufacturers using the new spillage test to identify appliances with problems and improve appliance performance. With this simple test, manufacturers can develop and market more spillage resistant combustion appliances. The appliances with the largest spillage for this research and the 2005 research were direct vent fireplace inserts.

CHAPTER 5:
Effects of Wind on House Depressurization and Vent Termination

Wind can affect house depressurization and combustion appliance venting. Some research has been conducted to determine the effects of wind on residential building depressurization; however, significantly less literature is available for effects of wind on vent caps. Commonly, wind flowing horizontally or upward over a chimney creates low pressure that produces increased draft. Wind blowing downward into the chimney or blowing against a nearby structure taller than the chimney can adversely affect draft. Additionally, the type of vent cap can have a significant effect on whether or not the combustion appliance vents properly while wind is present. Although many codes and standards (see Chapter 2 of this literature review) provide guidelines for vent and chimney termination design that help eliminate negative effects of wind on the vent exit, the only requirement stated about the vent cap is that each vent must have an appropriate vent cap. In the following sections, research investigating the effects of wind on internal pressure and the effects of wind on vent caps is summarized.

Effects of Wind on Internal Pressures

Holmes [29] measured the mean and fluctuating pressures inside buildings induced by high winds using a boundary layer wind tunnel and computer simulation techniques. He found that the mean fluctuating internal pressure coefficients increase monotonically with increasing windward/leeward open area ratio, which agreed with theory. For a single windward opening, wind tunnel measurements and computer simulated data showed resonance effects on the fluctuating internal pressures. The resonant frequency increases and the damping decreases with increasing open area. Additionally, resonant frequencies do not contribute greatly to the total root-mean-square (RMS) pressure fluctuations. The author implied that the effects of higher wind velocities can be simulated by distorting the internal volume by a factor equal to the square of the velocity ratio.

Stathopoulos et al. [50] experimentally investigated wind-induced internal pressures using models of low-rise buildings of different geometry and internal volume. Three basic models were constructed, each containing variable side-wall and end-wall openings as well as three background porosities (0%, 0.5%, and 3.0% of the total surface area). The results show that internal pressures fluctuate significantly, but the overall magnitudes are less than that of local external pressures. The gust factor (the ratio of the peak pressure to the mean) is approximately two in open country. Additionally, fluctuations in internal pressure show little or no spatial variation except in regions close to dominant openings. For windward openings, internal pressure coefficients are positive except for cases with high background porosity combined with small openings, in which case they become zero or negative. The largest internal pressures occur when the wind direction is perpendicular to the wall with the dominant opening. When the downwind side of the structure contains the dominant opening and the windward wall is closed, then the internal pressures are generally negative and insensitive to the size of the wall opening or the background porosity.

Modera and Wilson [38] examined the potential for reducing the effect of wind on fan pressurization measurements of air leakage. Their research does not investigate the effects of wind on overall house depressurization, but is still relevant to this literature review. Experiments were conducted using multiple fan-pressurization tests on a single test house under variable wind conditions. The results show that by incorporating time averaged pressure signals, time averaged flow signals, and four-wall surface-pressure averaging, unbiased leakage area measurements with a scatter less than 11% can be obtained from fan pressurization measurements at wind-speeds up to 5 m/s. The CGSB pressure-averaging probe generally caused a negative bias in the measured leakage area at high wind speeds. Modera and Wilson also show that choosing the appropriate reference for the indoor-outdoor pressure differential is critical for fan pressurization measurements. They recommend implementing noise-reduction filtering and averaging techniques to fan pressurization tests.

Effects of Wind on Vent Caps

The purpose of a vent cap is to prevent rain and debris from penetrating the venting system and to resist adverse effects cause by the wind. Many vent-cap designs claim to prevent downdrafting and wind driven rain entry. However, very little literature is available verifying the effectiveness of these vent caps.

UL 441 [52] provides requirements and tests for vent and vent cap design. It includes a test for determining the draft loss and wind effects on installed vent caps. The “Draft Loss and Wind Effects Test” is subdivided into three tests.

- The first test evaluates the vent cap impedance on flue flow for no wind. Static pressure inside the vent is measured with and without the vent cap. The difference in static pressure measurements cannot exceed 0.034 in.w.c (about 8.5 Pa).
- The second test evaluates the vent cap impedance on flue flow when subject to 20 mph wind conditions at a series of elevation angles ranging from 45 degrees below the horizontal to 45 degrees above the horizontal, in 15 degree intervals. Again, static pressure is measured inside the vent when uncapped and capped. The average difference in static pressure cannot not exceed 0.068 in.w.c. (about 17 Pa) at a horizontal wind front and at the three angles below horizontal or at a horizontal wind front and at the three angles above the horizontal.
- The third test evaluates the vent cap affect on the intended upward draft when subject to 20 mph wind conditions at a series of elevation angles ranging from 45 degrees below the horizontal to 45 degrees above the horizontal, in 15-degree intervals. For this test, the inlet to the gas vent is sealed so no air is flowing through the vent. Static pressure inside the vent is measured while wind is applied to the cap at different angles. The average pressure inside the vent must be equal to or less than 0.034 in.w.c. (about 8.5 Pa) below atmospheric pressure. Additionally, no pressure measurements can exceed atmospheric pressure.

Haysom and Swinton [27] were one of the first to report on the influence of flue caps (vent caps) on vent performance. They studied the effects of wind on four vent cap designs using a wind tunnel. The tests were conducted on common configurations of furnace and fireplace vent terminations to determine the horizontal and vertical wind pressure coefficients. Vent performance simulation results (likely from FLUESIM) were compared with experimental results. Three key features of a cap were identified: 1) its ability to moderate updraft in horizontal winds, 2) its ability to dampen the effects of updrafting or downdrafting winds, and 3) the amount of restriction to flow it creates. Three performance parameters were suggested based on key features of the cap: 1) the cap’s horizontal wind pressure coefficient, 2) the cap’s vertical wind pressure coefficient, and 3) the effective flow area (EFA) of the cap or chimney exit. Their results showed that with a 20 km/h (12 mph) wind speed, for almost all wind angles tested, the vent caps could develop more than enough driving pressure to counteract the most severe house depressurization. The authors recommended that vent caps be tested at various wind speeds and approach angles rather than at a single set condition, as outlined in UL 441. They also recommended that a rating system for vent caps be developed for choosing appropriate vent caps for given house conditions.

Han et al. [26] investigated “venturi-type” vent caps for exhaust fans. The purpose of their study was to improve vent cap design to minimize energy consumption by exhaust fans and improve performance. They compared their results to a vent without a vent cap. Wind speed was varied from 0 to 30 m/s, wind direction was varied from 0 to 90 degrees (0 degrees being parallel to the wall/roof surface), and exhaust pressure was varied from 0 to 100 Pa.

The ASHRAE Handbook – HVAC Systems and Equipment [1] provides some information regarding effects of wind on vent caps. The Handbook states that chimneys are required to be a minimum of 3 feet above the roof so small sparks will burn out before falling on the roof shingles. For satisfactory dispersion with low, wide buildings, chimney height must still be determined as if the height of the building is equal to the width of the building.

The Handbook also states that wind over a chimney can either impede or assist draft. If a chimney is located on the windward side of a wall or a steep roof, the wind can create a positive static pressure that impedes flow and results in backdrafting. Chimneys located near the surface of a less steep or flat roof can aid draft because the roof surface is under negative static pressure, but the wind velocity over the chimney is low. Taller chimneys experience greater wind velocity, which increases the draft. Because both chimney height and roof incline can affect chimney drafting, providing protocols for optimizing draft is difficult.

Pitched roofs can create either a positive or negative pressure over the chimney. According to the Handbook, the windward side of a roof with a pitch angle from 0 to 30º can create complete or partially negative pressures on the chimney or vent termination. The windward side of a 45º pitched roof creates strongly positive pressures on the chimney or vent termination. Steeper pitch roofs approach pressures observed on a vertical wall facing the wind. Wind velocities and pressures vary not only with pitch, but also with position between the ridge and eaves and in the horizontal direction of the pitched roof. Results for the leeward side are not presented. Tall chimneys exposed to full wind velocity can create strong venting updrafts. The updraft effect relative to wind dynamic pressure is related to the Reynolds number. If a vent cap is not present, then the open top can be sensitive to wind angle and rain. Proprietary vent caps have been designed to stabilize wind effects and improve performance.

Many compromises have been made in vent termination design, sacrificing some of the updraft created by the wind. According to the Handbook, the following performance features are important for vent cap design: still-air resistance, updraft ability with no flow, and discharge resistance when vent gases are carried at low velocity in a typical wind (3 m/s vent velocity in a 9 m/s wind). The Handbook also states, "test standards outlined by UL 441 take into account these aspects of performance to ensure adequate vent capacity." Additionally, vent caps with high still-air resistance should be avoided.

CHAPTER 6:
Patents Relating to Spillage and Backdrafting

Viner et al. [53] patented a design for a backdrafting alarm assembly for combustion heating devices. The alarm measures temperature at several locations around the draft hood of the combustion appliance. If temperatures exceed 130ºF over a sustained period (about 3 minutes), an alarm sounds.

Zimmermann et al. [56] patented a design for a flue gas sensor that continuously measures CO, NO_x, and O_2 located under the appliance draft hood near the exhaust outlet, but not directly in the exhaust stream. The inventors show a combustion appliance monitor design that is not affected by temperature so it can be directly inserted into the exhaust flow in the vent. If the monitor measures high amounts of CO, indicating spillage, then the monitor shuts off the appliance. Their sensor is mainly designed to measure hot exhaust gases from the vent and reduce the temperature of the exhaust gases before reaching the gas analyzer.

CHAPTER 7: Simulation Software for Combustion Appliance Venting Systems and House Ventilation

This chapter focuses on software that simulates venting, spillage, backdrafting, and/or depressurization. The chapter includes a brief description of various software packages and reviews literature on model validation.

Two software packages are available for simulating gas appliance venting. The first, VENT-II, is capable of predicting transient operation of venting systems serving one or two appliances. The second, FLUESIM, is capable of predicting the effect of the whole house system (including the envelope, chimney or vent, combustion appliance, exhaust appliances, weather, flue cap design) on venting performance of the combustion appliance.

Building envelope depressurization from wind and the use of mechanical systems can be modeled using CONTAM. CONTAM is capable of predicting building airflows, contaminant concentrations, and personal exposure. Further details for each software package are provided in the following sections.

Gas Appliance Simulation Software

VENT-II

VENT-II is a computer program designed to provide detailed analysis of gas appliance venting systems, including the transient effects of appliance cycling. The program calculates temperatures, pressures, flows, priming times (time it takes to heat up the vent system), and flue gas condensation throughout the vent system. The program is capable of modeling one or two fan-assisted or natural draft gas appliances on a single vent [18]. The program reportedly has been validated for common types of venting systems using venting guidelines for Category I gas appliances [47]. These venting systems include single-wall metal vents, Type B vents, plastic pipe vents, tile-lined masonry chimneys, and masonry chimneys that have been relined for use with gas appliances.

The first version of VENT-II was released for public purchase in 1991 and was labeled Version 4.1. Version 5.0 was released to operate using the Microsoft Windows 95/NT environment. The current version, 5.3, uses the same equations and code as Version 4.1, but is capable of operating using the Windows XP/Vista/7 environment. Additionally, Version 5.3 allows the user to print reports about the vent system being modeled and to export graphs and tables of simulation output for use in other programs. The appearance of graphs is also customizable.

VENT-II uses classical fluid flow, heat transfer, and mass transfer theory to predict venting performance, which includes calculating external natural convection, internal forced and natural convection, mass transfer of water vapor between the vent gas and the vent wall, condensation heat transfer, heat transfer through the vent wall, available draft, mass flow, and pressure loss.

The program calculates available draft using the difference between outdoor-air density and mean gas density in each section. The ideal gas law is assumed for calculating the vent gas density, which means the density is inversely proportional to vent gas absolute temperature. The draft in each vent region is calculated using:

$$Draft = \sum_{i=1}^{Ns} P_{nat}, \qquad (2)$$

where, $P_{nat} = (\rho_0 - \bar{\rho}_f)gH$, ρ_0 is the density of air outside the vent at the elevation of the vent section (kg/m^3) , $\bar{\rho}_f$ is the mean density of the vent gas in the vent section i (kg/m^3), g is the gravitational constant (m/s^2), H is the height of the vent section (m), and N_s is the total number of vent sections in the vent connector or common vent. Vent system performance parameters as a function of time are calculated by dividing the vent system into sections. A transient (time-varying) calculation is necessary for determining condensation in the vent system. The time step in VENT-II is fixed at 5 seconds.

For vent systems with two appliances, VENT-II can only predict vent flow for the scenarios listed in Table 33. VENT-II handles a single appliance as Appliance 1 and assumes Appliance 2 is fan-assisted with a very large loss coefficient in order to suppress the vent connector flow. Leakage at section joints is also calculated. Initial conditions assumed in VENT-II are summarized in Table 34.

Although VENT-II has been used for predicting vent system performance, cited validation reports were not easily obtained. A related article written by Rutz and Leslie [48] concludes that designing and constructing vent systems that follow protocols in the National Fuel Gas Code can resolve the majority of venting problems associated with fan-assisted gas appliances. However, VENT-II can be used to go beyond the scope of National Fuel Gas Code. One should note that the sizing tables provided in Chapter 13 of the National Fuel Gas Code [39] were generated using the VENT-II computer program.

Table 46: VENT-II Configuration Scenarios

Appliance Scenario Number	**Appliance 1**		**Appliance 2**	
	Type*	Operating State	Type*	Operating State
1	ND	Any	ND	Any
2	ND	Any	FA	Off
3	ND	Any	FA	On
4	FA	Off	FA	Off
5	FA	On	FA	Off
6	FA	On	FA	On

*ND = Natural Draft, FA = Fan-Assisted

Table 47: VENT-II Initial Conditions

Parameter	**Initial Condition**
Wall Temperature	Ambient Temperature
Heat Loss/Gain	None
Condensate	None
Flue Gas Temperature	Ambient Temperature
Flue Gas Flow	Zero
Flue Gas composition	Air
Vent System Draft	None
Vent System Flow, percent of on-cycle combustion flow rate	Draft-hood system: 30% Fan-assisted system: 10%

A more recent article written by Glanville et al. [21] provides research validating VENT-II by comparing VENT-II results with results from a computational fluid dynamics (CFD) software package (Fluent, Version 6.3). This study primarily focused on relining requirements related to upgraded venting systems with masonry chimneys. Performance of these chimneys was assessed using VENT-II, Fluent, and measured data. The authors stated that VENT-II is a one-dimensional nodal model, solving a reduced form of the Navier-Stokes equations and a semi-empirical condensation model at the interior flue surface. Fluent was setup using the k-ε turbulence model. Compared to Fluent, the authors state that VENT-II provided “sufficiently accurate” predictions for condensation. VENT-II, Fluent, and experimental results confirm the relining recommendations in the National Fuel Gas Code venting tables for the cases studied. In their results, they present data for condensation rates, but do not provide experimental or numerical data showing temperatures or pressures in the chimney. The authors state that temperature and pressure were measured during their experiments, but did not compare the measurements with VENT-II results.

FLUESIM

FLUESIM is a computer program developed for the Research Division of Canada Mortgage and Housing Corporation (CMHC) in the 1980's. It simulates a whole house "system", including the building envelope, chimneys, furnaces, and exhaust appliances. It can simulate a wide variety of indoor and outdoor conditions and was developed as a research tool for studying the performance of various furnace/flue systems and their interaction with the building and other mechanical systems. The program was originally used to gain a better theoretical understanding about indoor air quality problems related to combustion appliance backdrafting and spillage. FLUESIM can also be used to prevent circumstances that may lead to venting problems [49].

The program takes into account several different effects on venting performance including, but not limited to, size and mass of the vent connector and chimney, indoor and outdoor temperature difference, the flue location (interior or exterior), airtightness of the building, location of make-up air openings, cross-envelope flows, wind action at the top of the flue and on the envelope, presence of flue dampers and caps, and type of furnace (oil or gas). Experimental test data on flue caps is also provided for different wind angles and chimney material types. Although FLUESIM is a very powerful tool, it requires 180 user inputs to fully describe the system and conditions being simulated, making it impractical to use onsite [49].

A research house owned by CMHC was used to provide initial field data for validating the software. These data were then used to calibrate and fine tune FLUESIM. The user’s manual [49] does not contain data or experiments validating FLUESIM, but does include a list of background research papers that contain more information regarding the inner working of the model and its algorithms. The manual recommends a study conducted in 1987 [20] in which experimental data from 21 houses, identified to have spillage problems, were used to further validate FLUESIM. The program confirmed that many factors contributed to combustion venting problems and that venting problems with a chimney depend not only on its own characteristics and location, but also on the circumstances in which it is required to operate. The modeling and survey results also showed that spillage from conventional fireplaces is virtually certain in all but the leakiest houses and that conventional glass doors provide no additional protection against spillage.

Building Contamination, Depressurization, and Infiltration Simulation Software

CONTAM

CONTAM is a multizone indoor air quality and airflow network analysis computer program designed to determine:

- building system airflows: infiltration, exfiltration, and room-to-room flows driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by indoor, outdoor, and interzone air temperature differences.
- contaminant concentrations: the dispersal of contaminants transported by airflows; transformed by a variety of processes including chemical and radio-chemical transformation, adsorption and desorption to building materials, filtration, and deposition to building surfaces; and generated by a variety of source mechanisms.
- personal exposure: exposure of occupants to airborne contaminants for risk assessment.

CONTAM88 was a combination of the National Bureau of Standards (now the National Institute for Standards and Technology, NIST) pollutant transport (CONTAM87) and airflow network (AIRNET) simulation tools. CONTAM94 added a GUI to facilitate input entry. CONTAMW appeared in about 2000.

Since its original release, CONTAM has included several new features including contaminant-related libraries, separate weather and ambient contaminant files, building controls, scheduled zone temperatures, and an improved solver to reduce simulation time. CONTAM can simultaneously calculate multizone airflows and pressures to assess the adequacy of ventilation rates in a building, determine the variation in ventilation rates over time, and assess the impact of envelope air tightening on zone depressurization. The program requires inputs such as building component characteristics (e.g., zone nodal heights, flow path resistances and locations, duct leakage), weather, contaminant generation rates, and occupant locations and schedules. With these inputs, CONTAM can predict contaminant concentrations, which can be used to determine the indoor air quality performance of a building. Predicted contaminant concentrations can also be used to estimate personal exposure based on building occupancy patterns. Because CONTAM does not have an embedded thermal model, it is not capable of predicting venting performance, backdrafting events, or spillage events without being linked to a thermal model (e.g., VENT-II, FLUESIM, TRNSYS).

CHAPTER 8:
Literature Gaps and Conclusions

Established methods for evaluating the safety of residential combustion appliance venting systems produce results that are not directly relatable to risk. Current standard tests do not state a clear risk management objective, nor are they conducted in a manner that provides a clear indication of the risk of spillage during normal operation. A key deficiency is that they do not explicitly account for the fact that backdrafting and spillage are both physical and statistical phenomena. The zero risk tolerance implied in current standards may be harming energy efficiency efforts – by limiting air sealing – without appreciably increasing occupant safety. It is also possible that current test methods do not always identify problematic conditions.

Backdrafting and spillage occur when there is a confluence of contributing physical elements. Those elements include appliance and venting systems that are vulnerable to spillage based on sizing, materials, and configuration; characteristics of mechanical systems that contribute to house depressurization; appliance and other mechanical system use patterns; weather; and building component air tightness. Air sealing to improve envelope air tightness and the installation or upgrade of exhaust fans can both increase depressurization of interior spaces and thus increase the likelihood of backdrafting and spillage of natural draft combustion appliances. Combustion safety tests are employed to assess whether air tightening will or has created an untenable spillage hazard. Mitigation options include limiting air sealing – which sacrifices energy-savings potential directly – or installation of power-venting combustion appliances and/or some engineered capacity for make-up air; the latter measures may divert funds that could be applied to other measures that achieve greater energy efficiency benefits.

Induced stress tests that create nominal “worst case” conditions could be understood as seeking zero risk tolerance. Stress tests and long term monitoring approaches that allow (do not treat as failures) occurrences of transient spillage that occur just after the main burner ignites can still be regarding as having implicit no-risk targets; transient spillage events of a few minutes or less do not release enough pollutant mass to substantially impact indoor air quality. Specifying a clear risk mitigation objective is important when trying to assess if an appliance and venting configuration is problematic, and especially if a test is effective at finding problematic installations.

For a no-risk standard, there are two essential questions that are relevant to assessing the robustness of any specific test. (1) Does the test “fail” or identify as problematic, appliance and venting installations that do not produce sustained backdrafting and spillage in use? (2) Does the test “pass” or not identify as problematic some appliance and venting installations that actually produce sustained backdrafting and spillage during use? The former can be characterized as misleading test failures; the latter can be characterized as misleading passes. The concept of a misleading test result is also relevant to probability-based metrics.

As described in Chapter 4, most of the research assessing the performance of established methods involves comparing the results of different test methods applied to the same appliances. Monitoring under natural use conditions is logically understood to assess actual backdrafting and spillage. Consistent with this framework, the results of stress-induced tests typically have been evaluated in reference to monitoring results. Results from the studies that have employed this approach are inconclusive with respect to the two questions noted above. Most of the in-use monitoring has focused on houses failing stress-induced tests. Across the studies, varying but generally small fractions of houses that fail the stress tests are found to have backdrafting and spillage in practice. However, the one-week duration of monitoring that occurred in most of the published studies may be too short to reliably conclude that the studied appliances and houses will not have any incidences of spillage over the course of a typical year.

Extensive monitoring has not been conducted in houses that pass stress-induced tests. The reliability of such tests to identify all houses that are at risk is therefore unresolved.

A more productive research focus has been to identify characteristics of appliances, venting systems, and houses that fail the stress-induced tests. Key findings are that failures are often associated with improperly sized or installed venting systems, and/or improperly installed combustion equipment. Bohac and Cheple [7] found that venting systems that were properly sized and met code standards [39] were more likely to vent properly and pass stress-induced tests. Additionally, equipment that is serviced, tuned, and maintained is more likely to vent properly and produce less harmful pollutants, such as CO and NOx. Fugler [19] presented research suggesting that spillage events are more strongly correlated with appliance and venting system configuration than with effects of outside temperature and wind. Fugler additionally suggested that poor chimney performance is likely the largest contributing factor to combustion spillage. However, Fugler did not provide data showing the effects of wind and temperature on stress-induced tests.

Existing research examining the link between combustion spillage with occupant health is limited. According to a study conducted by Wilson et al. in 1993 [54], 95% of homes (277 total) tested continuously over 48 hours met the maximum 1-hour and 8-hour CO limits. The maximum 1-hour and 8-hour California standards for CO are 20 ppm and 9 ppm, respectively. A report investigating non-fire CO deaths associated with consumer products from 2007 [28] states that 2% of the 184 CO related deaths (from 2005 to 2007) were caused by water heaters, 2% were caused by ranges and ovens, 14% were caused by furnaces, and 17% were caused by other heating systems (i.e., portable, unvented heaters). These results suggest that acute CO poisoning from vented combustion appliances is extremely rare. However more research is required to investigate both acute and chronic CO poisoning associated with vented combustion appliances.

The effects of weather variation, especially for wind, on stress-induced test methods have not been adequately assessed in published research. Despite the large research efforts to date, the tests and standards currently in use are insufficient for predicting if natural and unsealed induced-draft combustion appliances are venting safely. Research conducted by Koontz et al. [34] is the only available research focusing on how weather conditions affect stress test results. Their results showed that houses were more likely to fail stress tests during low wind speeds than high wind speeds; however, more research needs to be conducted to further understand the relationship between wind speed and venting performance. The authors did not find a definitive correlation between outdoor temperature and stress tests, but did suggest that water heaters are more likely to fail when outside temperatures exceeded 60°F. Bohac and Cheple [7], however, showed spillage failure increased significantly when the outside temperature exceeds 40°F. Because little research is available assessing the relationship between outdoor temperature and stress test failure, more research is required.

Haysom and Swinton [27] showed that vent caps performed well at wind speeds of about 12 mph and were able to establish draft even when the house was depressurized. However, no research is available assessing vent cap performance under low or zero wind conditions. UL 441 requires vent caps to meet specified requirements for wind speeds of 0 and 20 mph at different angles, but might be accepting vent caps that could be problematic under low wind conditions or in some locations where local static pressures are increased due to wind stagnation or deflection by adjacent surfaces. In some cases, because vent caps are not tested for their performance over a range of wind conditions, appliance drafting could be competing with downdrafting caused by presence of low wind conditions, but draft properly if no wind or high wind was present. Further investigation is required for testing the performance of vent caps under a range of wind conditions, especially low wind conditions.

In principle, the likelihood of backdraft and spillage can be assessed for a wide range of equipment and venting configurations and weather using either of the two existing simulation software programs: VENT-

II or FLUESIM. However, we found no published reports of either program being applied for this purpose. Even basic documentation about the performance of these programs in comparison to experiments is lacking in the archival literature. VENT-II provides outputs for sizing vent systems, but does not take into account effects of wind or depressurization of the combustion appliance zone. Additionally, validation reports for VENT-II are difficult to obtain. FLUESIM provides outputs for predicting spillage, but reports showing how it was validated are difficult to obtain. CONTAM is a useful tool for determining CAZ depressurization, but CONTAM cannot independently predict combustion appliance performance, backdrafting, or spillage. Further research exploring the use of these computer programs for predicting venting performance, backdrafting, and spillage is required.

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